ISSN 0254-5284

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# The use of saline waters for crop production

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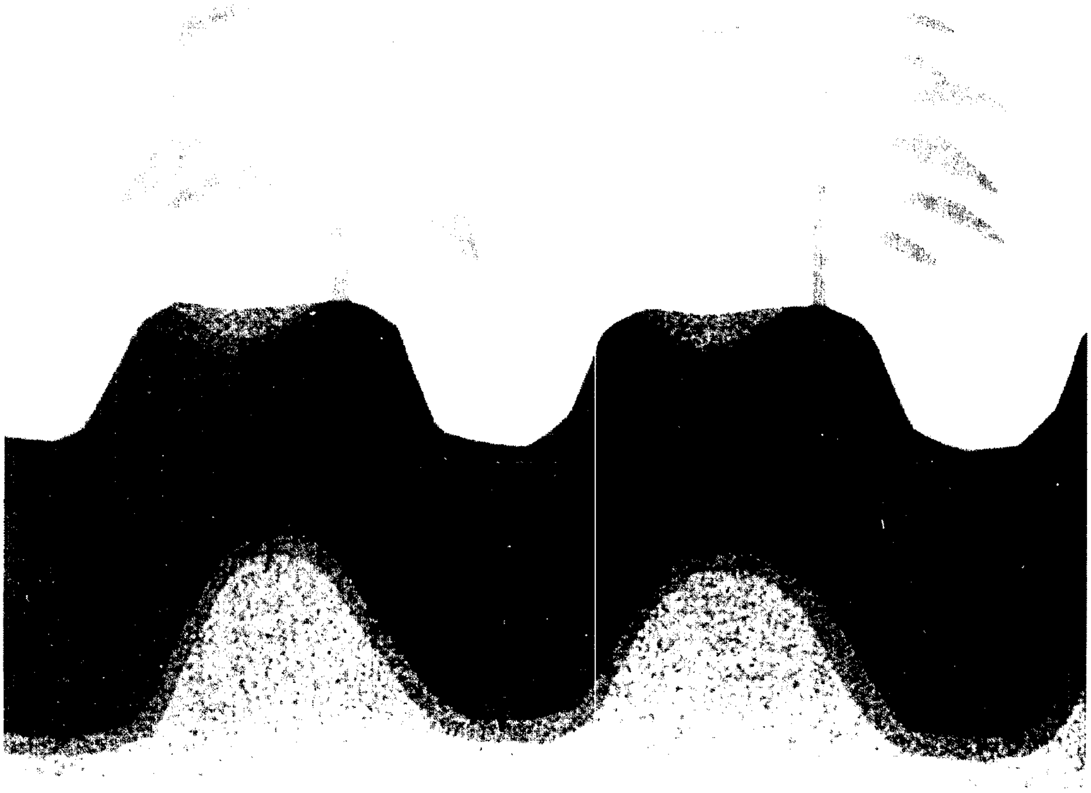

FOOD
AND
AGRICULTURE
ORGANIZATION
OF THE
UNITED NATIONS

# The use of saline waters for crop production

FAO IRRIGATION AND DRAINAGE PAPER

48

by
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FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS
Rome, 1992

M-56
ISBN 92-5-103237-8

# Preface

The challenges of poverty and hunger remain as great and compelling as ever. The number of the world's under-nourished is still on the increase, despite the remarkable progress made in agricultural development in developing regions in recent years. Increasing food production to meet the needs of the increasing world population on a sustainable basis remains the primary goal of all nations.

In this context the importance of irrigated agriculture needs no emphasis. Currently, production from the irrigated lands, which constitute about 17 percent of the total arable lands, accounts for 35 percent of the global food harvests. Irrigation has the ability not only to increase production per unit area of land but also to stabilize production. Indeed many countries will look to irrigated agriculture as the only reliable means to increase production on a sustainable basis.

However, irrigation requires water and this is an essential commodity in increasingly short supply. There is now growing realization that an increasing number of countries are approaching full utilization of their conventional surface water resources and that the quantity of good quality water supplies available to agriculture is diminishing. What is left is water of marginal quality such as saline groundwater and drainage waters. The question that needs to be answered is: "can agriculture make use of marginal quality water such as saline water in a way that is technically sound, economically viable and environmentally non-degrading; in other words, is it a viable proposition to use saline water for agricultural production?"

FAO convened an Expert Consultation in October 1989 to seek answers to these pertinent questions. A few very select experienced and "dyed in the wool" professionals in the subject area analysed the current status of saline water use in irrigation and examined water, soil and crop management techniques relating to the use of saline water for crop production. The conclusion of the Expert Panel was that there is good potential for the safe use of saline water for crop production. The Panel recommended the integrated management of water of different qualities at the levels of the farm, irrigation system and drainage basin, with the explicit goals of increasing agricultural productivity, achieving optimal efficiency of water use, preventing on-site and off-site degradation and pollution and sustaining long-term production potential of land and water resources.

This publication, "The use of saline waters for crop production: guidelines on water, soil and crop management", is written by three experts who participated in the Expert Consultation. In preparing this publication, they have drawn heavily on the papers presented in the Expert Consultation as well as on the recommendations that came out of the Consultation. It is hoped that this publication will provide guidelines to many developing as well as developed countries in order that they may manage their saline waters for productive purposes in a sustainable manner.

# Acknowledgements

This guidelines publication is an outcome of a FAO Consultation on "Water, Soil and Crop Management Relating to the Use of Saline Water" held in 1989 in Rome. A number of ideas and the conceptual framework of the guidelines were developed at this Consultation. The authors wish to acknowledge the resource persons of the consultation, namely Messrs. I.P. Abrol (India), A. Hamdy (Italy), A. Meiri (Israel) and A.H.M. Rady (Egypt) who have contributed to this publication through the Expert Consultation.

A good part of the research findings reported in these guidelines has come from the United States Salinity Laboratory, Riverside, California, and the authors gratefully acknowledge the staff of the Laboratory for their outstanding contribution.

The authors wish to express their gratitude to Mr. S.F. Scott, Chief, Water Resources, Development and Management Service, and Mr. R. Brinkman, Chief, Soil Resources, Management and Conservation Service, for their support and encouragement in the preparation of the guidelines. A number of people have reviewed the document and proofread the text; the authors are grateful to them.

Thanks are also due to Ms. C.D. Redfern for her assistance in the preparation of the final camera-ready text and to Mr. D. Mazzei for the revision of the illustrations.

It is hoped that the guidelines will be useful to the many research and extension workers and the farmers who currently use, or will use in the future, the largely untapped resource of "saline water" for agriculture in a sustainable manner.

**USEFUL CONVERSION FACTORS AND FORMULAS**

| | |
|---|---|
| TDS (mg/l) ≈ EC (dS/m) x 640 | for EC between 0.1 and 5.0 dS/m |
| TDS (mg/l) ≈ EC (dS/m) x 800 | for EC $<$ 5.0 dS/m |
| TDS (lbs/ac-ft) ≈ TDS (mg/l) x 2.72 | |
| TDS (tons/ac-ft) ≈ TDS (mg/l) x 0.00136 | |
| sum of cations/anions (meq/l) ≈ EC (dS/m) x 10 | for EC between 0.1 and 5.0 dS/m |

log cations/anions ($mmol_c$/l) ≈ 0.955 + 1.039 log EC (dS/m)

log total soluble salts ($mmol_c$/l) ≈ 0.990 + 1.055 log EC (dS/m)

ionic strength (mol/l) ≈ EC (dS/m) x 0.0127

osmotic pressure (atm) ≈ EC (dS/m) x 0.40 for EC between 3 and 30 dS/m

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# List of abbreviations

SAR = sodium adsorption ratio
EC = electrical conductivity
$EC_{iw}$ = electrical conductivity of irrigation water
$SAR_{sw}$ = sodium adsorption ratio of soil water
dS/m = deciSiemens per metre
$mmol_c/l$ = millimol per litre
$EC_e$ = electrical conductivity of soil saturated extract
TDS = total dissolved soilds
mg/l = milligrams per litre
BCM = billion cubic metres
MCM = million cubic metres
ESP = exchangeable sodium percentage
$Y_r$ = relative yield
T = tolerant crop
MT = moderately tolerant crop
MS = moderately sensitive crop
S = sensitive crop
$g/m^3$ = grams per cubic metre
RSC = residual sodium carbonate
$EC^*_e$ = water uptake weighted electrical conductivity of soil saturation extract
$\pi$ = osmotic potential
$\pi^*$ = water uptake weighted osmotic potential
adj. SAR = adjusted sodium adsorption ratio
$\tau$ = metric water potential
$\overline{\phi}$ = total water potential
$\overline{C}$ = mean salt concentration
$V_{iw}$ = volume of infiltrated irrigation water
$V_{dw}$ = volume of drainage water
LF = leaching fraction
$C_{iw}$ = salt concentration of irrigation water
$C_{dw}$ = salt concentration of drainage water
$\bar{\tau}$ = mean metric water potential
$\phi_f$ = total water potential at any given point for irrigation scheduling
kPa = killiopascal
$pCO_2$ = partial pressure of carbon dioxide (pascal Pa)

# Executive summary

The primary objective of these guidelines is to facilitate the safe use of saline waters for crop production, while promoting water conservation and environmental protection. A secondary objective is to create an awareness of the degradational and pollutional consequences that result from prevalent irrigation practices and the potential to minimize these problems through the interception, isolation and reuse of drainage water for irrigation employing appropriate strategies and practices. In this publication "saline waters" refers to natural salt-affected waters as well as those resulting from human activities, such as irrigation with drainage waters and shallow groundwaters, that fall in the range of 1500 to 7000 mg/l total dissolved solids and which are not widely used for irrigation. Cropping considerations will generally require that appropriate management practices be employed to use such waters effectively over time for crop production.

These guidelines are addressed primarily to those involved with irrigated agriculture, soil and water conservation, and environmental protection. Emphasis is on the avoidance of waterlogging and secondary salinization problems (both in soils and water supplies) associated with irrigation. The basis for these guidelines is presented in terms of the principal effects of salts and irrigation practices on soils, waters and crops.

## SCOPE

Chapter 1 discusses the potential to use saline waters, especially drainage waters, to increase crop production (particularly in those countries which are limited by available water supplies) while simultaneously helping to overcome environmental pollution problems associated with irrigation and drainage. Quality characteristics, sources and availability of saline waters potentially suitable for irrigation are described in Chapter 2. Examples of the successful use of various saline waters for irrigation under widely varying situations around the world are given in Chapter 3 to lend credibility to the Guidelines recommendations for such use. In Chapter 4, criteria, standards, methods and models to assess the suitabilities of saline waters for irrigation are discussed. The nature and causes of waterlogging and soil salinization, water pollution, eco-system disturbance and water-borne diseases associated with irrigation are reviewed in Chapter 5. Management principles and practices for safe use of saline waters for crop production and environmental protection are discussed in Chapter 6.

## SALINE WATERS AS A RESOURCE

There is ample evidence to illustrate the widespread availability of saline waters and a wide range of experience exists around the world with respect to using them for irrigation under different conditions. This evidence and experience demonstrates that waters of much higher salinities than those customarily classified as "unsuitable for irrigation" can, in fact, be used effectively for the production of selected crops under the right conditions.

## EFFECTS OF SALTS ON CROP PRODUCTION

Salts exert both general and specific effects on plants which directly influence crop growth and yield. Salts also affect certain soil physico-chemical properties which, in turn, affect the suitability of the soil as a medium for plant growth. Excess sodium and very high pH, such as might occur with the use of saline- sodic waters for irrigation, promote the slaking of aggregates and the swelling and dispersion of clays which lead to soil crusting, loss of porosity and reduced permeabilities, especially when rapid desalinization occurs following rainfall or the subsequent use of low-salinity waters for irrigation. The major general effect of salts on plants is to reduce plant stand and growth rate. Chloride, sodium and boron may exert specific toxicity effects on susceptible crops, especially woody perennials. Plants vary in their tolerances to salts and many are sufficiently tolerant, especially after seedling establishment, to produce well when irrigated with saline waters, especially typical drainage waters, provided appropriate cultural management practices are followed.

## ASSESSING THE SUITABILITY OF SALINE WATER FOR CROP PRODUCTION

The suitability of a water for irrigation should be evaluated on the basis of criteria indicative of its potential to create soil conditions hazardous to crop growth and subsequently to animals or humans consuming those crops. Relevant criteria for judging irrigation water quality in terms of potential hazards to crop growth are primarily:

- **Permeability and tilth**
- **Salinity**
- **·Toxicity and nutritional imbalance**

Permeability and crusting hazards are evaluated by electrical conductivity ($EC_{iw}$) and the sodium adsorption ratio predicted to occur in the topsoil after irrigation ($SAR_{sw}$) with reference to threshold tolerances (permissible combinations of $EC_{iw}$ and $SAR_{sw}$) established for the specific soil in question or, in the absence of specific information, an appropriate general relation. $SAR_{sw}$ is predicted using a computer model (such as Watsuit, which is used in this publication) or, in the absence of a computer, using the SAR value of the irrigation water ($SAR_{iw}$).

Salinity, toxicity and nutritional problems are evaluated by comparing levels of soil water salinity, concentrations of toxic ions and ratios of Ca/Mg predicted (with Watsuit) to result in the rootzone of the soil after irrigation with reference to acceptable values of salinity, toxic-ion concentrations and Ca/Mg ratios for the specific crop(s) in question. Tables of acceptable levels of salt and toxic-ion concentrations are provided for many crops and plants. Predictions of soil salinity resulting from irrigation with a given saline water can also be made without benefit of a computer by ignoring salt precipitation and dissolution reactions.

Tables and figures are provided to make such predictions along with examples of their use for assessing saline water suitability for irrigation. Uncertainties in the model predictions and insufficient knowledge of soil and crop responses to salts and toxic ions limit the exactness and quantitativeness of the assessment procedure.

## ENVIRONMENTAL ASPECTS OF IRRIGATION

In a number of countries, irrigated agriculture has resulted in major environmental disturbances such as waterlogging and salinization, depletion and pollution of water supplies, especially groundwaters, and increased health risks. The recreational, aesthetic and habitat values of many water systems and agricultural landscapes have also been degraded by improper irrigation development and practices.

Most of the problems of waterlogging and secondary salinization prevalent in irrigated lands and of associated water pollution have resulted from the excessive use of water for irrigation as a consequence of inefficient irrigation distribution systems and poor on-farm management practices, inappropriate drainage management, and the discharge of "spent" drainage water into good-quality water supplies. These problems have occurred even where low salinity waters have been used for irrigation. This might lead one to conclude that the use of saline waters for irrigation can only increase these problems. However, this is not necessarily the case.

The use of saline waters of the levels advocated herein for irrigation will not result in excessively saline soils *per se* nor cause waterlogging with proper management. In fact, the interception of drainage waters percolating below rootzones and their reuse for irrigation will reduce the soil degradational processes associated with excessive deep percolation, salt mobilization, waterlogging and secondary salinization that typically occur in irrigated lands and the water pollution problems associated with their discharge to good-quality water supplies.

In considering the use of a saline water for irrigation and in selecting appropriate management to protect water quality, it is important to recognize that the total volume of a saline water supply cannot be beneficially consumed for irrigation and crop production; and the greater its salinity, the less it can be consumed before the salt concentration becomes limiting. The practice of blending or diluting excessively saline waters with good quality water supplies should only be undertaken after consideration is given to how this affects the volumes of consumable water in the combined and separate supplies. Blending or diluting drainage waters with good quality waters in order to increase water supplies or to meet discharge standards may be inappropriate under certain situations. More crop production can usually be achieved from the total water supply by keeping the water components separated. Serious consideration should be given to keeping saline drainage waters separate from the "good quality" water supplies, especially when the latter waters are to be used for irrigation of salt-sensitive crops. The saline drainage waters can be used more effectively by substituting them for "good quality" water to irrigate certain crops grown in the rotation after seedling establishment.

## MANAGEMENT PRINCIPLES AND PRACTICES TO CONTROL SALINITY

An integrated, holistic approach is needed to conserve water and prevent soil salinization and waterlogging while protecting the environment and ecology. Firstly, source control through the implementation of more efficient irrigation systems and practices should be undertaken to minimize water application and reduce deep percolation. Unavoidable drainage waters should be intercepted, isolated and reused to irrigate a succession of crops of increasing salt tolerance, possibly including eucalyptus and halophyte species, so as to reduce drainage water volumes further and to conserve water and minimize pollution, while producing useful biomass. Conjunctive use of saline groundwater and surface water should also be undertaken to aid in lowering water table elevations, hence to reduce the need for drainage and its disposal, and to conserve water. Various means should be used to reclaim or to dispose of the ultimate unusable final drainage effluent.

To achieve these goals, new technologies and management practices must be developed and implemented. Efficiency of irrigation must be increased by the adoption of appropriate management strategies, systems and practices and through education and training. Such measures must be chosen with recognition of the natural processes operative in irrigated, geohydrologic systems, not just those on-farm, and with an understanding of how they affect the quality of soil and water resources, not just crop production. Some practices can be used to control salinity within the crop rootzone, while other practices can be used to control salinity within larger units of management, such as irrigation projects and river basins. Additional practices can be used to protect offsite environment and ecological systems - including the associated surface and groundwater resources.

There is usually no single way to achieve salinity control in irrigated lands and associated waters. Many different approaches and practices can be combined into satisfactory control systems; the appropriate combination depends upon economic, climatic, social, as well as edaphic and hydrogeologic situations. Thus, no procedures are given for selecting "the" appropriate set of control practices for different situations. They are too numerous. Rather, some important goals, principles and strategies of salinity management, at both on-farm and project levels, that should be considered in the selection and implementation of control practices are reviewed and discussed.

# Chapter 1

# Introduction

One of the primary objectives of agriculture is to provide the food and fibre needs of human beings. These needs increase as the population increases. The world population was 2.5 thousand million in 1950; 4.9 thousand million in 1985, and 5.3 thousand million in 1990. It is expected to be 6.3 thousand million in 2000, and 8.5 thousand million in 2025 (UN 1991). The population of the developing countries, which is presently over three-quarters of the worlds total, is projected to increase by about 2.0 percent per year during the last decade of this century and to account for about 90 percent of the expected increase in global population (World Bank 1988). These growth rates will require an increase in agricultural production of about 40 to 50 percent over the next thirty to forty years, in order to maintain the present level of food intake; a 20 and 60 percent increase for developed and developing countries, respectively.

Growth in crop production can come from increases in arable land, cropping intensity and yield per unit area of cropped land. Nearly two-thirds of the increase in crop production needed in the developing countries in the next decade must come from increases in average yields, a fifth from increases in arable lands, and the balance from increases in cropping intensity (FAO 1988). About two-thirds of the increase in arable lands is expected to come from the expansion of irrigation. Thus it is concluded that the needed increases in food production in developing countries must come primarily from existing cropland, mostly irrigated land.

Irrigation has already played a major role in increasing food production over the past fifty years. The world's irrigated land was 8 million hectares in 1800, 48 million hectares in 1900, 94 million hectares in 1950 198 million hectares in 1970, and about 220 million hectares in 1990 (Jensen *et al.* 1990). About three-quarters of the irrigated land is presently in the developing countries. In these countries, almost 60 percent of the production of major cereals (primarily rice and wheat) is derived from irrigation. Irrigated land presently accounts for 15 percent of the cultivated land but produces 36 percent of the world's food (FAO 1988).

Expansion in irrigation needs to be 2.25 percent per year in order to meet food needs by the year 2000 (FAO 1988). However, the present rate of expansion in irrigation has recently slowed to less than 1 percent per year (CAST 1988). The reasons for this slowing down in expansion rate are many. Among them are the high costs of irrigation development and the fact that much of the suitable land and water supplies available for irrigation have already been developed; progressively more expensive and socio-economically less favourable areas are left for further expansion. Water is the limiting constraint for almost 600 million hectares of potentially suitable arable land (FAO 1988). Also, the overall performance of many irrigation projects has been less than expected due to inadequate operation, maintenance and inefficient management (FAO 1990). It is not unusual to find that less than 60 percent of the water diverted or pumped for irrigation is actually used in crop transpiration. Furthermore, improper irrigation causes environmental and ecological problems.

Agricultural production systems are limited by the capacity of the associated eco-systems to sustain their natural properties, even though advances in agricultural technology (including use of irrigation, plant breeding, fertilizers and pesticides) have reduced our dependency somewhat in this regard. The relationship between sustainable agriculture and the environment is one of complimentarity and interdependence. In many locations around the world, strains upon the environment are occurring increasingly and concern is mounting about the sustainability of irrigated agriculture with respect to waterlogging, salinization, erosion, desertification, loss of biological diversity, water-borne diseases, adverse effects of potentially toxic agricultural chemicals upon human health and the biota of associated eco-systems (World Commission on Environment and Development 1987).

Overall, the use of sophisticated agricultural practices has had, so far, a net beneficial effect upon agricultural production, human welfare, nutrition and health. But mismanagement and overuse have the potential to overwhelm the ability of natural processes to "absorb" these practices. A critical challenge facing most countries is to halt and reverse the present extent of environmental degradation resulting from excessive exploitation of natural resources, especially those manifested in desertification, soil erosion, waterlogging, and soil and water salinization, in order to ensure the needs of future generations. Presently, 5 to 7 million hectares of arable land (0.3 - 0.5 percent) are being lost every year through soil degradation. The projected loss by the year 2000 is 10 million hectares annually (0.7 percent of the area presently cultivated). By the year 2000, productivity of about one-third of the world's arable land may be severely impaired by excessive erosion (UNEP 1982). The future expansion of food production will be increasingly dependent upon sound irrigation and water management and upon the concurrent maintenance of the present agricultural resource base and the environment - two of the most challenging tasks facing mankind today (FAO 1988).

From the facts and projections cited above it is concluded that:

- global food needs are increasing while soil and water resources are becoming more limited and diminished in quality;
- the need to conserve water, to utilize it more efficiently and to protect its quality, and simultaneously to protect soil resources is increasing; and
- world agriculture must both expand its base of production and produce more with presently developed resources.

Because higher yields are obtained with irrigated agriculture and because it is less dependent on the vagaries of weather, it assumes special importance in this regard. Expansion of irrigated agriculture could contribute significantly towards achieving and stabilizing food and fibre needs. However, new water supplies for such expansion are limited. Irrigated agriculture is already the largest consumer of developed water resources. At the same time, drainage return from irrigated lands is one of the major causes of waterlogging (usually in lower lying regions) and of water pollution (with respect to salts, nitrates, agricultural chemicals and certain natural, potentially toxic trace elements).

Water availability for irrigation could be enhanced through judicious and proper use of saline water and the recycling of drainage waters for irrigation. Considerable amounts of such water are available in various places in the world, including Australia, Egypt, India, Israel, Pakistan, the USA, and the former USSR. Waters generally classified as unsuitable for irrigation can, in fact, be used successfully to grow crops without long-term hazardous consequences to crops or soils, with the use of improved farming and management practices. The development of crops with increased salt tolerance and the adoption of new crop and water management strategies will further enhance and facilitate the use of saline waters for irrigation and crop production, while keeping soil salinity from becoming excessive. The reuse of drainage waters for irrigation will also help to conserve water and to minimize the hazardous effects of irrigation on the environment and ecology.

The development of appropriate practices for the use of saline waters for irrigation requires an adequate understanding of how salts affect waters, soils and plants. But, the sustainability of a viable, permanent irrigated agriculture, especially with the use of saline irrigation waters, requires much more. It requires the implementation of appropriate management practices to control salinity, not only within the irrigated fields, but also within irrigation projects and geohydrologic systems. It is important to remember that most waterlogging and salinity problems presently existing in major irrigation projects throughout the world have resulted with the use of "good quality" irrigation waters. Hence, it may be argued that the major causes of salinity problems presently being generally encountered in typical irrigation projects must first be avoided, if more saline than normal waters are to be used successfully for irrigation, since such use may increase the likelihood of salinity problems in a given field. On the other hand, reuse of drainage waters for irrigation can help reduce overall the drainage, waterlogging and salt-loading problems that occur, especially at the project or river basin scales and, hence, can result in a net decrease in the totality of irrigation-induced and salinity-related problems, including environmental pollution. In any case, it is imperative that management practices for the control of soil and water salinity at such scales be considered an essential part of the management requirements for using saline waters for irrigation. This requires the following:

- that the seriousness of salinity-related environmental problems and the vulnerability of irrigated lands to waterlogging and salination be sufficiently recognized;

- that the processes contributing to these problems and the effects of salts on soils and plants be understood;

- that the salinity conditions and trends of the irrigated lands and associated water resources be routinely assessed using appropriate measurement and monitoring techniques that provide meaningful and timely information;

- that salinity-related problems be properly diagnosed using appropriate criteria and standards;

- that future conditions of soil and water salinity be adequately predicted using appropriate prognostic techniques; and

- that the viability of the irrigated agriculture and associated water resources be sustained by implementing effective long-term control measures.

# Chapter 2

# Saline waters as resources

## QUALITY CHARACTERISTICS OF SALINE WATERS

Chemical and physical characteristics of irrigation waters are discussed in detail by Ayers and Westcot (FAO 1985). Hence, only brief descriptions of terminology, units and key parameters are given in this publication. The parameters of relevance, in this case, are restricted to those which predominantly affect crop production either directly or indirectly. The limiting values of the quality parameters vary considerably depending upon circumstances of use. Sewage and industrial effluents are not considered as the focus of these guidelines is on irrigation with drainage waters and moderately saline natural waters of various kinds. An abbreviated classification of waters in terms of salinity is given to facilitate the identification of the kinds of saline waters included in the scope of these guidelines.

### Definitions and Indices of Salinity Related Parameters

The term salinity used herein refers to the total dissolved concentration of major inorganic ions (i.e. Na, Ca, Mg, K, $HCO_3$, $SO_4$ and Cl) in irrigation, drainage and groundwaters. Individual concentrations of these cations and anions in a unit volume of the water can be expressed either on a chemical equivalent basis, $mmol_c/l$, or on a mass basis, mg/l. Total salt concentration (i.e. salinity) is then expressed either in terms of the sum of either the cations or anions, in $mmol_c/l$, or the sum of cations plus anions, in mg/l. For reasons of analytical convenience, a practical index of salinity is electrical conductivity (EC), expressed in units of deciSiemen per metre (dS/m). An approximate relation (because it also depends upon specific ionic composition) between EC and total salt concentration is 1 dS/m = 10 $mmol_c/l$ = 700 mg/l. Electrical conductivity values are always expressed at a standard temperature of 25°C to enable comparison of readings taken under varying climatic conditions. With all its obvious shortcomings, this custom of using EC as an index of salinity emphasizes the concept that, as a good first approximation, plants respond primarily to total concentration of salts rather than to the concentrations or proportions of individual salt constituents.

A similar usage of EC for expressing soil salinity has evolved, where the parameter of primary interest is the total salt concentration, or EC, of the soil solution. However, the content of water in the soil is not constant over time nor is the composition of the soil solution. For this reason, soil salinity is not an easily defined, single-valued parameter. In an attempt to standardize measurements and to establish a reasonable reference for comparison purposes, "soil salinity", is commonly expressed in terms of the electrical conductivity of an extract of a saturated paste ($EC_e$; in dS/m) made using a sample of the soil.

In addition to total salt concentration, sodium and pH can adversely affect soil properties for irrigation and cropping. At high levels of sodium relative to divalent cations in the soil solution, clay minerals in soils tend to swell and disperse and aggregates tend to slake, especially under conditions of low total salt concentration and high pH. Whether from slaking, swelling or from clay dispersion, the permeability of the soil is reduced and the surface becomes more crusted and compacted under such conditions. Thus the ability of the soil to transmit water can be severely reduced by excessive sodicity (the term used herein to refer to the combined deleterious effects of high sodium and pH, and low electrolyte concentration on soil physical properties). Since high total salt concentration tends to increase a soil's stability with respect to aggregation and permeability, distinction is made between saline soils and sodic soils. With respect to sodicity, it is the proportion of adsorbed exchangeable sodium relative to the cation exchange capacity (often expressed as the exchangeable sodium percentage, ESP), rather than the absolute amount of exchangeable sodium, that is relevant along with the total salt concentration of the infiltrating and percolating water and the soil pH. Because ESP and the sodium adsorption ratio of the saturation extract ($SAR = NA/\sqrt{(Ca+Mg)/2}$, where solute concentrations are in $mmol_c/l$) are so closely related, SAR is commonly used as a substitute for ESP and as an index of the sodium hazard of soils and waters.

Certain ions in saline waters can be specifically toxic to plants, if present in excessive concentrations or proportions. Of particular concern are sodium (Na), chloride (Cl), and boron (B). While not often toxic to plants, a few solutes sometimes (though not frequently) found in natural saline waters may accumulate in plant parts at levels that can be toxic to consumers, if their diet is largely restricted to this food. Such elements include selenium (Se), arsenic (As), and molybdenum (Mo). Standards for such specific toxicants in waters are usually given in terms of their individual concentrations (FAO 1985).

## Classification of Saline Waters

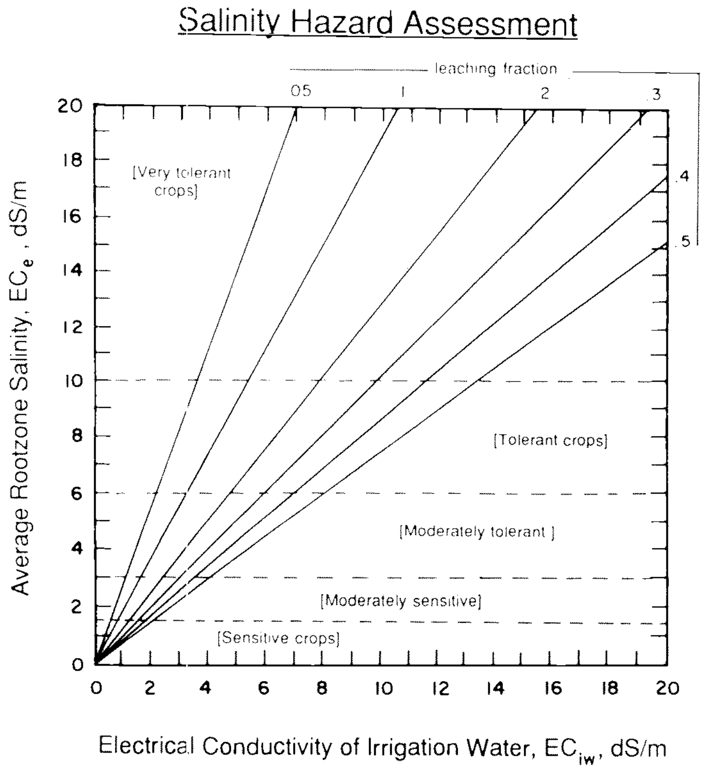
Because the suitability of a saline water for irrigation is so dependent upon the conditions of use, including crop, climate, soil, irrigation method and management practices, water quality classifications are not advised for assessing water suitability for irrigation. However, for the purpose of identifying the levels of water salinities for which these guidelines are intended, it is useful to give a classification scheme.

Such a classification is given in Table 1 in terms of total salt concentration, which is the major quality factor generally limiting the use of saline waters for crop production. As seen in Figure 1, only very tolerant crops (hardly any conventional crops) can be successfully produced with waters that exceed about 10 dS/m in EC. Few generally-used irrigation waters exceed about 2 dS/m in EC. Many drainage waters, including shallow groundwaters underlying irrigated lands, fall in the range of 2-10 dS/m in EC. Such waters are in ample supply in many developed irrigated lands and have good potential for selected crop production, though they are often not used in this regard and are more typically discharged to better quality surface waters or to waste outlets. It is the use of such saline waters that is the major focus of these guidelines. Reuse of second-generation drainage waters for irrigation is also sometimes possible and useful, especially for purposes of reducing drainage volume in preparation for ultimate disposal or treatment. Such waters will generally have ECs in the range 10-25 dS/m. Thus, they too are considered in these guidelines, though to a much lesser degree because the "crops" that can be grown with them are atypical and much less experience exists upon which to base management recommendations and to develop guidelines. Very highly saline waters (25 - 45 dS/m in EC) and brine (> 45 dS/m in EC) are beyond the scope of these guidelines and their uses for crop production are therefore not discussed herein.

TABLE 1
**Classification of saline waters**

| Water class | Electrical conductivity dS/m | Salt concentration mg/l | Type of water |
|---|---|---|---|
| Non-saline | <0.7 | <500 | Drinking and irrigation water |
| Slightly saline | 0.7 - 2 | 500-1500 | Irrigation water |
| Moderately saline | 2 - 10 | 1500-7000 | Primary drainage water and groundwater |
| Highly saline | 10 - 25 | 7000-15 000 | Secondary drainage water and groundwater |
| Very highly saline | 25 - 45 | 15 000-35 000 | Very saline groundwater |
| Brine | >45 | >35 000 | Seawater |

**Figure 1**
**Relationships between $EC_e$ (saturation extract basis), $EC_{iw}$ and leaching fraction under conventional irrigation management (after Rhoades 1982)**



## SOURCES AND AVAILABILITY OF SALINE WATERS

In practical agricultural use, a common source of saline water is groundwater. Salinity of groundwater can be man-induced or natural.

In many areas, saline and fresh subsurface waters exist in close proximity. When fresh groundwater is pumped from aquifers that are in hydraulic connection with seawater, the change in gradients as a result of pumping may result in a flow of salt water from the sea towards the well. This is called seawater intrusion.

Upconing is another mechanism by which groundwater could become brackish. Upconing refers to a situation where a well, located close enough to saline water underlying freshwater, is pumped at a rate sufficient to cause the salt water to be drawn into the well in an upward shaped cone or mound. It has been estimated that in the USA over two-thirds of the continental area are underlain by saline groundwater that could intrude on freshwater supplies as a result of upconing.

There are also natural causes of salinity. Numerous investigators have noted that water within sedimentary strata becomes increasingly saline with an increase in depth. In general, the sequence noted is sulphate-rich water near the surface, saline bicarbonate water at an intermediary level and more concentrated chloride water at greater depths (Craig 1980). There are several mechanisms by which water trapped in sedimentary rocks can be altered into saline water. One of these is the solution of sediments and rocks.

In coastal regions, surface water sources can become saline due to the tidal influence of the sea. As the high tide moves into the coastal area, seawater moves into streams and drainage canals and travels inland. This upstream migration of seawater alters the quality of water in affected streams and drainage canals significantly. This phenomenon is also observed during times of drought.

Another important source of saline water is drainage effluent (including perched groundwater) from irrigated areas. Drainage water, once thought of as wastewater, is now used in many countries for irrigation. The salinity levels vary, but often the salt levels are higher than those of conventional primary irrigation water sources. Reuse of drainage effluent is important when the supply of good quality irrigation water is limited, and it is also an efficient means of reducing water pollution.

The use of saline drainage water in Egypt was reported by Abu-Zeid (1988). About 2.3 thousand million $m^3$ of drainage wastewater are discharged annually to the Mediterranean Sea via return to the Nile River in Upper Egypt; 12 thousand million $m^3$ are discharged directly into the sea and northern lakes; 2 to 3 thousand million $m^3$ are used for irrigating about 405 000 ha of land. About 75 percent of the drainage water discharged into the sea has a salinity of less than 3000 mg/l. The policy of the Government of Egypt is to use drainage water directly for irrigation if its salinity is less than 700 mg/l; to mix it 1:1 with Nile water (180 to 250 mg/l) if the concentration is 700 to 1500; or 1:2 or 1:3 with Nile water if its concentration is 1500 to 3000 mg/l; and to avoid reuse if the salinity of the drainage water exceeds 3000 mg/l. The potential disadvantages of such blending are discussed later.

Drainage water is used for crop production on many farms in California, USA. For example, saline subsurface drainage water is blended with Delta-Mendota Canal water in the Broadview Water District of California to form blended water of a salinity equivalent to 3.2

dS/m and since 1956 is used to grow a variety of crops. Over time, the cropping pattern in this district has changed as the water quality has decreased. Crops now grown are mostly cotton, barley and alfalfa. Representative salinities and potentials for use as irrigation waters and drainage waters from the major irrigated areas of the USA are described by Rhoades (1977).

The use of brackish groundwater is reported from Tunisia, India and Israel. De-Malach *et al.* (1978) state that in the central Negev of Israel, sugarbeet is grown with saline groundwater of EC = 4.4 dS/m under sprinkler irrigation.

Gupta (1990) has treated the subject of saline water use in India comprehensively. He reported that the salinity level of the Ganges river in India is very low and average total dissolved salt concentration is less than 200 mg/l. However, there are specific stretches or locations along the river system where salinity level increases due to hydrologic as well as human-induced activities. In the deltaic region of the Ganges river in West Bengal, which comes under tidal influences, the salinity of the water can rise to greater than 10 times the average salinity of the river.

In the Punjab, Maharashtra area, canal waters are reported to be of good quality with EC values often less than 0.5 dS/m. On the other hand, drainage waters are reported to have high salinities. Prasad (1967) reported that the drainage waters of the Unnao Tehsil in Uttar Pradesh had an average EC of 2 dS/m. Gupta (1990) carried out a survey of groundwater quality in Rajasthan and estimated percentages of wells that fall into varying classes of salinity. The results are presented in Table 2.

TABLE 2
**Percent distribution of groundwaters of Rajasthan in different EC classes**

| EC range dS/m | 11 arid districts (2817)[1] | 7 semi-arid districts (4000)[1] | 8 humid districts (2614)[1] |
|---|---|---|---|
| <0.75 | 10 | 23 | 41 |
| 0.75-2.25 | 29 | 48 | 49 |
| 2.25-5.00 | 27 | 19 | 8 |
| 5.00-10.0 | 20 | 8 | 2 |
| 10.0-15.0 | 9 | 2 | - |
| >15.0 | 5 | - | - |

1 Number of samples

# Chapter 3

# Examples of use of saline waters for irrigation

A selected review of some representative examples of the commercial use that has been made of saline waters for irrigation under different circumstances around the world follows. The examples were chosen to be representative of the worldwide experience of such use and because relevant information, including water quality, climate, soil type, crops, irrigation systems and methods, other management practices, yields and period of use, was available. These reviews supplement those given elsewhere (Rhoades 1990a) and serve to illustrate the wide range of experience that exists in using saline water for irrigation under different conditions and to demonstrate that waters of much higher salinities than those customarily classified as "suitable for irrigation" can, in fact, be used effectively for the production of selected crops under the right conditions. They also illustrate some of the management practices that have been found to be effective to facilitate such use.

## UNITED STATES OF AMERICA

In the USA, saline waters have been successfully used for irrigation for periods of from 75 to 100 years in several areas of the Southwest, including the Arkansas River Valley of Colorado, the Salt River Valley of Arizona, and the Rio Grande and Pecos River Valleys of New Mexico and West Texas (Erickson 1980). Representative compositions of three of the irrigation waters used in these areas are given in Table 3 (see Water Nos. 1, 2 and 8 - 10). The principal crops grown in these areas are cotton, sugarbeet, alfalfa and small grains. According to Erickson, the "farming community of the Southwest has demonstrated that it is possible to adjust to the use of whatever water is available ... as long as other factors permit irrigated agriculture to continue ...". The following discussion gives more detail for some of these areas.

In the Pecos Valley of West Texas, groundwater averaging about 2500 mg/l TDS, but ranging far higher (at least to 6000 mg/l), has been successfully used to irrigate about 81 000 hectares of land for three decades (Moore and Hefner 1977; Miyamoto *et al.* 1984). A typical composition is given in Table 3 (see Water No. 2). In this Valley, the rainfall is less than 300 mm, most of which occurs in showers of less than 25 mm. The major crops include cotton, small grains, grain sorghum and alfalfa. The soils are calcareous (pH 7.5 to 8.3) with a calcium carbonate equivalent of between 20 and 30 percent; they are also low in organic matter and show little structural development. Soil textures range from silt loams to silty clay loams. Infiltration rates average about 0.5 cm per hour. Internal drainage is good; water tables are usually below 3 m. The soils display slaked-aggregate conditions immediately

TABLE 3
**Composition of some saline waters successfully used for irrigation**

| Constituent | Water Nos. | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| Ca $mmol_c/l$ | 18.8 | 11.6 | 5.6 | 10.0 | 12.8 | 2.5 | 1.4 | 22.6 | 27.2 | 25.0 | 14.5 | 28.9 |
| Mg $mmol_c/l$ | 15.7 | 9.3 | 2.3 | 5.5 | 8.8 | 3.9 | 3.6 | 9.7 | 13.6 | 9.4 | 7.4 | 21.2 |
| Na $mmol_c/l$ | 25.2 | 19.4 | 28.9 | 20.0 | 34.0 | 12.4 | 41.3 | 50.7 | 74.8 | 78.2 | 26.3 | 50.0 |
| K $mmol_c/l$ | - | 0.4 | - | - | - | 0.4 | - | - | - | - | - | - |
| $HCO_3$ $mmol_c/l$ | 5.1 | 4.1 | 7.4 | 2.4 | 2.2 | 4.6 | 9.6 | 2.4 | 1.8 | 15.6 | 4.1 | 5.0 |
| $SO_4$ $mmol_c/l$ | 50.6 | 9.2 | 8.1 | 18.0 | 21.2 | 4.6 | 1.2 | 29.3 | 37.9 | 29.7 | 32.7 | 67.0 |
| Cl $mmol_c/l$ | 4.1 | 27.0 | 20.6 | 14.0 | 19.6 | 12.6 | 35.2 | 19.7 | 34.5 | 32.8 | 11.4 | 28.0 |
| $NO_3$ $mmol_c/l$ | 0.5 | - | - | - | - | - | - | - | - | - | - | - |
| Total mg/l | 4200 | 2558 | - | - | - | - | - | 3206 | 4652 | 4850 | - | - |
| B mg/l | - | - | - | - | - | - | - | - | - | - | - | - |
| EC dS/m | 4.3 | 4.1 | 3.2 | 3.2 | 5.3 | 2.3 | 5.6 | 5.1 | 7.5 | 6.9 | 4.2 | 7.1 |
| SAR $(mmol_c/l)^{1/2}$ | 6.1 | 6.0 | 15.0 | 7.2 | 10.0 | 6.9 | 26.0 | 4.6 | 7.6 | 10.6 | 8.0 | 10.5 |
| pH | 7.7 | 7.8 | 7.5 | - | - | 8.2 | - | - | - | - | 8.3 | 8.1 |

**Table 3** Cont'd

| Constituent | Water Nos. | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 |
| Ca $mmol_c/l$ | 7.35 | 4.6 | 11.4 | 11.7 | 26.0 | 9.4 | 14.4 | 8.75 | 17.0 |
| Mg $mmol_c/l$ | - | 2.9 | 11.8 | 1.2 | 13.0 | 5.1 | 9.3 | 6.9 | 8.4 |
| Na $mmol_c/l$ | - | 0.1 | 33.6 | 3.4 | 50.6 | 11.7 | 25.3 | 27.9 | 6.2 |
| K $mmol_c/l$ | - | 0.1 | 0.3 | 0.1 | 0.2 | 0.5 | 0.6 | - | - |
| $HCO_3$ $mmol_c/l$ | 14.2 | 2.9 | 5.0 | 1.6 | 2.5 | 1.0 | 2.2 | 5.5 | - |
| $SO_4$ $mmol_c/l$ | 10.9 | 9.2 | 26.9 | 1.9 | 37.8 | 5.2 | 14.4 | 10.7 | 21.7 |
| Cl $mmol_c/l$ | 12.2 | 4.3 | 23.5 | 2.8 | 49.5 | 13.5 | 23.6 | 26.8 | 7.7 |
| $NO_3$ $mmol_c/l$ | - | - | - | - | - | - | - | - | - |
| Total mg/l | 2700 | - | - | - | - | - | - | - | - |
| B mg/l | - | 0.3 | 3.0 | 0.1 | 6.0 | - | - | - | 4.0 |
| EC dS/m | 3.6 | 1.5 | 4.6 | 0.7 | 7.9 | 1.8 | 3.0 | 4.2 | 2.5 |
| SAR $(mmol_c/l)^{1/2}$ | 5.8 | 6.1 | 10.0 | 2.9 | 11.4 | 5.3 | 7.3 | 10.0 | 1.7 |
| pH | - | 7.9 | - | - | - | - | - | 7.7 | - |

1 Arkansas River, near Granada, Colorado, USA (Miles 1977)
2 Well water Pecos Valley of West Texas, USA (Moore and Hefner (1977)
3 Representative well water SW Arizona, USA (FAO 1985)
4 Blended drainage water, Broadview Water District, California, USA (Tanji 1977)
5 Medjerda River, Tunisia, in dry season (Van't Leven and Haddad 1968)
6 Irrigation water used for vegetable production in United Arab Emirates (Savva *et al.* 1984)
7 Nahal Oz well water, Israel (Hadas and Frenkel 1982)
8 Irrigation water used near Carlsbad, New Mexico, USA (Erickson 1980)
9 Irrigation water used near Red Bluff, Texas, USA (Erickson 1980)
10 Irrigation water used near Hudspeth, Texas, USA (Erickson 1980)
11 & 12 Irrigated waters used in lysimeter experiment (Jury *et al.* 1978)
13 Tubewell used in field-plot experiment (Bhatti 1986)
14 & 15 Colorado River and drainage waters used under commercial and experimental conditions (Rhoades *et al.* 1989a)
16 & 17 California aqueduct and well waters used together in small-plot experiment (Rhoades *et al.* 1980)
18 & 19 Water used for irrigation at beginning and end of season in plot experiment in Italy (Fierotti *et al.* 1984)
20 Well water used in field plot experiment in Texas, USA (Thomas *et al.* 1981)
21 Waste water used in field experiment in Utah, USA (Hanks *et al.* 1984)

TABLE 4
**Representative composition of irrigation waters used in the major irrigated area of the Far West** (after Miyamoto *et al.* 1989)

| | Middle Rio Grande Area | | | Trans-Pecos Area | | |
|---|---|---|---|---|---|---|
| | Project water | Well water (El Paso) | Well water (Hudspeth) | Van Horn Valentine | Dell City | Pecos |
| EC dS/m | 1.1 ± 1 | 3.8 ± 1 | 7.0 ± 2 | 0.6 ± 0.3 | 3.7 ± 1 | 4.4 ± 2 |
| TDS mg/l | 800 | 2800 | 5140 | 380 | 2720 | 3230 |
| Na mmolc/l | 6.0 | 21.0 | 43 | 4.3 | 13.0 | 18.0 |
| Ca | 4.3 | 9.8 | 16.0 | 1.2 | 20.0 | 23.0 |
| Mg | 1.3 | 3.2 | 9.5 | 0.5 | 14.0 | 11.0 |
| $HCO_3$ | 3.8 | 4.4 | 3.7 | 2.4 | 2.7 | 1.8 |
| Cl | 3.0 | 19.0 | 48.0 | 1.0 | 17.0 | 16.0 |
| $SO_4$ | 5.0 | 13.0 | 15.0 | 1.8 | 25.0 | 32.0 |
| SAR (mmolc/l)½ | 3.6 | 8.2 | 12.0 | 4.7 | 3.1 | 4.4 |

following rainfall; the resulting crusting often necessitates replanting of crops, if it occurs during the seedling establishment period. Generally the $EC_e$ of the major rootzone is not more than 2 - 3 times that of the electrical conductivity of the irrigation water ($EC_{iw}$), about the same as $EC_{iw}$ below the furrow and up to about 6 times $EC_{iw}$ in the seedbeds.

Cotton is grown successfully with a gypsiferous water of up to 8 dS/m EC using alternate-row, furrow irrigation and double-row plantings on wide beds or by using single-row plantings on narrow beds and then "decapping" the peaks of the beds to remove resulting salt crusts prior to seedling emergence. Sprinkler irrigation of cotton is carried out during night or twilight hours using water of up to about 5 dS/m in EC. Alfalfa and several other forages are produced with minimal yield losses using waters of up to 3 to 5 dS/m, as have been tomatoes. Representative compositions of these waters are given in Table 4. Representative cotton yields are given in Table 5. Alfalfa yields in saline areas near Dell City have been 12.3 to 13.4 t/ha, whereas yields of 17.9 to 20.1 t/ha are common in the van Horn area.

Traditionally, most field crops in Far West Texas have been irrigated by furrow methods. When saline water is applied to every furrow, the highest salt concentration occurs in the ridge of the bed and the lowest concentration occurs beneath the furrow. This accumulation of salt in the bed often causes seedling mortality, or reduced germination. To minimize such salt accumulation, alternate-furrow irrigation is frequently used in the Trans-Pecos area. Under this system, salts are "pushed" towards the non-watered furrows. In the Hudspeth irrigation district, where irrigation water salinities are quite high, this method is usually used for the first one or two irrigations, thereafter every furrow is irrigated so as to prevent excessive salts from eventually accumulating under the dry furrows. Dragging the top of single-row, round-top beds with a chain or metal rod shortly before crop emergence is a practice undertaken in the El Paso Valley to prevent salt crust damage to emerging seedlings. This method also eliminates the soil crust that often develops in clay-textured soils after rains or excessive sprinkler irrigation. This method appears to work well with cotton and chilli peppers, but not so well with fast-emerging shallow seeded crops such as lettuce.

Double-row planting on flat beds is practised with lettuce, onions and in some cases with cotton. Seeds are planted on the edges of the bed where salt accumulation is minimal.

TABLE 5
**Representative yields of cotton in El Paso and Hudspeth portions of the Middle Rio Grande Basin** (after Miyamoto *et al.* 1984)

| Year | Yield in bales/acre (540 kg/ha) | | | |
|---|---|---|---|---|
| | Upland | | Pima | |
| | El Paso | Hudspeth | El Paso | Hudspeth |
| 1975 | 0.93 | 0.73 | 0.44 | 0.47 |
| 1976 | 1.26 | 1.18 | 0.99 | 0.94 |
| 1977 | 1.28 | 1.46 | - | 1.11 |
| 1978 | 1.54 | 1.16 | 1.16 | 0.60 |
| 1979 | 0.70 | 0.81 | 0.89 | 0.69 |
| 1980 | 1.05 | 1.07 | 1.13 | 0.72 |
| 1981 | 1.22 | 1.42 | 0.83 | 1.09 |
| 1982 | 1.18 | 1.14 | 1.31 | 1.33 |
| Average | 1.14 | 1.00 | 0.96 | 0.87 |

NB: Areas involved in El Paso and Hudspeth districts are on average 3000 and 1500 ha for Upland-cotton, and 6500 and 1500 ha for Pima-cotton, respectively.

Excellent stand and production of cotton have been obtained using this system with water of 5.4 dS/m in EC. This practice does not prevent seedling damage caused by saline-water splash associated with light rains and the presence of high surface accumulations of salts near the seedlings. Planting seed in the water-furrow is advantageous because the lower levels of salinity that occur there, but this practice has serious disadvantages as well. As soil in the furrow crusts badly and is colder, seedling diseases and weed infections are worse. Thus this method is used only in extremely saline soils for the establishment of some forage crops. Sprinkler irrigation in the Trans-Pecos region has been used mostly for alfalfa and forage crops. When the irrigation water salinity is as high as is found in this region, foliar-induced salt damage is sometimes a problem. In the Dell City area, alfalfa leaves frequently show margin leaf-burn, although no major yield reductions are reported, when sprinkler-irrigated with water of up to 3.0 to 5.0 dS/m in EC. Sprinkler irrigation of cotton is also used in several areas of the Trans-Pecos. A 15 percent reduction in lint yield typically results when cotton is sprinkled during the daytime with water of 4 dS/m in EC. Severe leaf burn and extremely poor yields result from daytime sprinkling with saline water having an EC of 5.0 dS/m. In both cases, no significant yield reduction is observed when such waters are applied at night.

A linear, mobile system that delivers water directly into the furrows (which often contain micro-dams) at low pressures of 34 - 55 kPa through "drop-tubes" from an overhead boom, rather than through spray nozzles which wet the plants as with conventional sprinkler methods, has more recently become popular in the area, because foliar damage from use of the saline water and water losses through wind-drift are largely avoided with this system. Yields of cotton obtained with this system have been equal to or greater than those of conventionally, furrow-irrigated cotton, even when using water of up to 8 dS/m in EC.

In summary, the experience in Far West Texas shows that good crop production of suitable crops can be achieved with use of saline waters (up to about 8 dS/m in EC) for irrigation if care is taken to obtain stand.

Saline groundwaters (ranging in EC from 3 to 11 dS/m; see Water No. 3 of Table 3) have been used successfully for irrigation for decades in some hot, dry regions of Arizona (Dutt *et al.* 1984). The fields are typically planted to cotton and germinated using water from lower salinity wells and alternate-furrow irrigation. Irrigations using the saline well waters are given after germination. The seasonal averaged irrigation water salinities and crop yields of four surveyed fields are given in Table 6. All these yields are near the value of 1238 kg/ha which is the statewide average yield of lint cotton, though the maximum yield is about

2310-2500 kg/ha in the absence of any serious yield-limiting factor. These data demonstrate that the successful commercial production of suitable crops is possible even in a hot, dry climate and when using relatively saline, sodium/chloride-type irrigation waters.

TABLE 6
**Irrigation water salinities and lint cotton yields at four locations in Red Mountain Farms, Arizona** (after Dutt *et al.* 1984)

| Parameters | A | B | C | D |
|---|---|---|---|---|
| Yield kg/ha | 1614 | 995 | 834 | 1076 |
| Water salinity dS/m | 6.2 | 4.5 | 4.0 | 11.1 |

O'Leary (1984) has shown in pilot-sized operations that several halophytes (such as *Atriplex nummalaria*) have potential for use as crop plants and can be grown with seawater. Yields of forage have been achieved which exceed the average yield of conventional crops, like alfalfa, irrigated with freshwater. The most productive halophytes yielded the equivalent of 8 to 17 metric tonnes of dry matter per hectare. These yields contributed the equivalent of 0.6 to 2.6 metric tonnes of protein per hectare, which compares to that obtained for alfalfa irrigated with fresh water. These halophytes yield even more when grown with water of lower salinity. For example, about double the above yields were obtained using water of 10 000 mg/l TDS for irrigation. Some halophytes, such as *Salicornia*, appear to have even better potential as oil seed crops. The use of secondary drainage waters for the growth of such crops after their first use for more conventional crops would facilitate the disposal of drainage waters by reducing the ultimate volume needing such disposal, as proposed by Rhoades (1977) and van Schilfgaarde and Rhoades (1984). Limited commercial use of such halophytes is now being attempted in various places in the world, but insufficient long term results are available to document its success.

## ISRAEL

Considerable use has been made of saline waters for irrigation in Israel. The majority of the saline groundwaters range between 2 and 8 dS/m in EC (about 1200 to 5600 mg/l in TDS). The average annual evapotranspiration is about 20 000 $m^3$ per hectare. Average annual rainfall exceeds 200 mm in over half of the country and is about 500 mm in the main agricultural area (600 mm in the coastal plain); most of the rain falls in the winter season. The climate is Mediterranean with a moderately hot, dry summer (April to March). Heavy dews occur in many parts of the country, especially near the coast. Mostly sprinkler or drip irrigation is used. The soils are generally permeable and drainage is good. Much of the saline water is introduced into the national carrier system; thus it is diluted before use. Because most of the crops are irrigated by sprinkler methods, some crops suffer poor emergence related to crusting. Thus they are sometimes started by furrow irrigation. Extra water (equivalent to about 25 to 30 percent in excess of evapotranspiration) is typically given for leaching. According to Israeli general recommendations, light- and medium-textured soils can be irrigated with any saline water in the range of the salinity tolerance of the crop, and heavy soils can be irrigated with waters having EC values of up to 3.5 to 5.5 dS/m where artificial drainage is provided (gypsum applications are advised for such waters). Cotton is successfully grown commercially in the Nahal Oz area of Israel with saline groundwater of 5 dS/m in EC and 26 of SAR (see Water No. 7 in Table 3) provided the silty clay soil is treated annually with gypsum and national carrier water is used (usually during the winter) to bring the soil to field capacity through a depth of 150 to 180 cm prior to planting (Frenkel and Shainberg 1975; Keren and Shainberg 1978).

## TUNISIA

The saline Medjerda River water of Tunisia (average annual EC of 3.0 dS/m; see Water No. 5 in Table 3) is successfully used to irrigate date palm, sorghum, barley, alfalfa, rye grass and artichokes. The soils are calcareous (up to 35 percent $CaCO_3$) heavy clays with low infiltration rates, especially after winter rainfall. During the growing season large cracks form (fissures of up to 5 cm in width) as the soil dries, subsequently permitting water to enter rapidly when first irrigated. Winter rainfall produces leaching of salts only to depths in the soil of about 15 cm. However, with properly timed irrigations and use of appropriate crops, such saline waters are being successfully used in Tunisia for the irrigation of even such relatively impervious soils (Van't Leven and Haddad 1968; van Hoorn 1971).

In 1962, the Tunisian Government created a Research Centre for the Utilization of Saline Waters for Irrigation (CRUESI), with the assistance of the Special Fund of the United Nations and Unesco. A technical report describes their findings through 1969 (Unesco/UNDP 1970). This work was carried out at the scale of commercial farming operations to ascertain how various crops would yield when irrigated in various ways (all surface methods) with saline waters. Experiment stations were chosen to be representative of the various combinations of soils, climates and irrigation water compositions prevalent in Tunisia. The soils varied in texture from light to heavy, the irrigation waters varied in salinity from 2000 to 6500 mg/l TDS and the rainfall varied from 90 to 420 mm. The SAR values of the waters were low (usually less than 10) and boron was not a problem. Representative compositions of the well waters used for irrigation are given in Table 7. The following is a summary of the major conclusions reported by this research team.

TABLE 7
**Representative compositions of saline irrigation waters studied in Tunisia (after Unesco/UNDP 1970)**

| | Stations | | | | |
|---|---|---|---|---|---|
| | Ksar Gheriss | Tozeur | Messaoudia | Nakta | Zarsis |
| EC dS/m | 4.9 | 3.1 | 2.8 | 5.5 | 9.2 |
| TDS mg/l | 4000 | 2100 | 2000 | 3800 | 6500 |
| pH | 7.5 | 7.7 | 7.6 | 7.6 | 7.9 |
| SAR (mmolc/l)½ | 7.1 | 6.3 | 6.1 | 11.7 | 24.8 |
| Ca mmolc/l | 18.0 | 9.0 | 11.2 | 13.5 | 14.8 |
| Mg mmolc/l | 15.5 | 6.7 | 3.1 | 7.5 | 6.2 |
| NA mmolc/l | 29.0 | 17.6 | 16.3 | 37.8 | 81.3 |
| K mmolc/l | 0.6 | 0.6 | 0.5 | 0.5 | 0.8 |
| Cl mmolc/l | 20.9 | 17.6 | 12.4 | 36.7 | 70.2 |
| $SO_4$ mmolc/l | 37.9 | 13.0 | 14.4 | 20.8 | 32.6 |
| $HCO_3$ mmolc/l | 3.2 | 2.4 | 3.8 | 3.0 | 2.1 |

The chemical content and composition of the irrigated soils become stable after about four years of irrigation, subject to variation in crop rotation effects. Sodicity does not become a significant problem. Winter rainfall can be effectively exploited for leaching purposes by keeping the soil high in water content just prior to rain events. (It should be noted that rainfall is higher in the coastal regions of Tunisia than is typical of most semi-arid regions; furthermore, much of the rainfall occurs in relatively intense storms in the winter months.) Good yields of appropriate crops can be obtained with use of typical well waters for irrigation (though with some reduction relative to the use of freshwater) provided certain precautions are taken. Salinity in the irrigation waters is concluded not to be an insurmountable barrier.

It primarily affects the summer crops whereas the winter crops are more strongly influenced by amount of rainfall and initial level of salinity present in the soil in the autumn of the year. Germination and emergence (especially the latter) are crucial to the success of cropping and establishment of stand is the major bottleneck. The physical condition of the soil surface layer has a major effect on emergence and methods of irrigation and tillage are very influential in this regard and given too little attention compared to salinity in management considerations. Poor aeration is a major problem when excessive amounts of irrigation water are given, such as might be encouraged when saline waters are used.

These Tunisian studies point out the need to pay close attention to other factors besides salinity *per se* (some of which, however, are influenced by salinity) which must also be controlled if successful irrigation with saline waters is to be achieved.

## INDIA

Crops are successfully grown in some parts of India under conditions quite different from those existing in typical, semi-arid regions. Much of the research and experience in India through 1980 has been summarized by Gupta and Pahwa (1981). Of particular benefit to the continued use of saline waters for irrigation in parts of India are the monsoon rains. It has been observed that very saline waters can be used for irrigation in these areas without excessive long-term build-up of soil salinity because of the extensive seasonal leaching that occurs there (Pal *et al.* 1984; Jain 1981; Manchanda and Chawla 1981; Tripathi and Pal 1979). These findings illustrate the high potential to gain benefit from the use of quite saline waters for irrigation in regions which receive sufficient rainfall to prevent the build-up of excessive soil salinity over time.

A field survey made during the period 1983-1985 showed that extensive use (104 000 shallow tubewells pumping 106 000 hectare-metres of water per year) is being made (since about 1975) of shallow-saline groundwater of EC up to 8 dS/m for irrigation in nine districts of Haryana State India (Boumans *et al.* 1988). In four of the districts, the saline water is solely used for irrigation, while in the remaining five it is used either after it is blended with fresh canal water or in alternation with the canal water. Mean rainfall in these areas ranges between 300 and 1100 mm. The soils are dominantly sandy loam in texture. Shallow water tables exist and surface flooding occurs following the monsoons. Table 8 presents the yield reductions found in a survey of the districts for the dominant crops when irrigated solely with the tubewell waters of the indicated levels of salinity. Only a few wells had EC values exceeding 7 dS/m, hence it appears that this level is about the maximum that the farmers have found to be acceptable for long-term use. Yield depressions of 30-40 percent are apparently acceptable to these farmers. The farming practices being used were not given, so it is not possible to evaluate whether opportunities may exist to improve yields through the adoption of modified practices. Still it is obvious that saline waters have been used successfully, even as the sole supply, for irrigation in these districts of India. Whether their

TABLE 8
**Representative yields (in %) by crop and irrigation water salinity in survey of Hissar area of Haryana, India** (after Boumans *et al.* 1988)

| Crop | Tubewell salinity, EC in dS/m | | |
|---|---|---|---|
| | 2-4 | 4-6 | 6-8 |
| Cotton | 100 | 70 | 55 |
| Millet | 100 | 79 | 52 |
| Wheat | 100 | 89 | 60 |
| Mustard | 100 | 86 | 67 |
| Average | 100 | 81 | 59 |

and vegetables. In the Delta, saline waters of EC 2.5 to 4 dS/m has been used successfully to grow vegetables under greenhouse conditions. In the New Valley (Oases, Siwa, Bahariya, Farafra, Dakhla and Kharga) there is potential to irrigate about 60 000 ha utilizing groundwater (salinity ranging from EC 0.5 dS/m to 6.0 dS/m), of which 17 000 ha are already under cultivation. Siwa Oasis has the largest naturally flowing springs in the New Valley. Siwa once contained a thousand springs, of salinity ranging from EC 2 to 4 dS/m, which were used successfully to irrigate olive and date-palm orchards, with some scattered forage areas. At present 3600 ha are irrigated from about 1200 wells. Of these 1000 are hand dug to depths of 20-25 m (salinity ranging from EC 3.5 to 5.0 dS/m and in some locations as much as 10 dS/m), and the remaining 200 wells were drilled deep (70-130 m) with salinity of EC 2.5-3.0 dS/m — the SAR values varying from 5 to 20. Presently about 235 MCM/year is being used successfully to irrigate olive and date-palm orchards, alfalfa, cereals and wood trees (of which 60 MCM from continuing flowing springs). Due to over-irrigation without appropriate drainage facilities, seepage as well as run off to low lying land, salinity and waterlogging have developed in some lands of the oasis.

To reduce drainage water volumes, minimize water pollution and safely dispose of the ultimate unusable final drainage water, new strategies are being developed and experimented by the Government authorities in Siwa Oasis (similar problems exist in Dakhla oasis). These include:

- use of natural flowing springs to irrigate winter crops such as cereals and forage;
- use of saline water over 5 dS/m to irrigate salt tolerant crops like barley, vetches, Rhodes grass, sugarbeet, etc.;
- use of biologically-active drainage water for the production of windbreak and growing wood trees;
- use of drainage water for stabilization of sand dunes;
- reuse of drainage water (average salinity is EC 6.0 dS/m with SAR values of 10 to 15) after blending with good quality water (recently drilled deep well of salinity EC 0.4 dS/m with SAR of 5) or by alternating the drainage water with good water.

use could be better facilitated by blending or alternating with freshwater supplies is discussed later.

## EGYPT

Egypt is a predominantly arid country and the scattered rain showers in the north can hardly support any agricultural crops. Agriculture thus depends mainly on irrigation from the River Nile (55.5 BCM per year). The needed increase in food production to support the acceleration of population growth (2.7%), compels the country to use all sources of water (i.e. drainage water, groundwater and treated sewage water) for the expansion of irrigated agriculture.

The policy of the Egyptian Government is to use drainage water (up to salinity of 4.5 dS/m) after it is blended with fresh Nile water (if its salinity exceeds 1.0 dS/m) to form blended water of a salinity equivalent to 1.0 dS/m. The drainage water presently used for irrigation amounts to 4.7 BCM per annum and it is likely to increase to 7 BCM per annum by the year 2000 (see Table 9).

TABLE 9
**Quantity of drainage water, salinity levels and estimated reuse in years 1988 and 1992**
(adapted by Mashali based on data reported by Amer and Ridder (1988) and Rady (1990)

| Regions | Quantity of drainage water in MCM | | | | | Total | Estimated reuse | |
|---|---|---|---|---|---|---|---|---|
| | Salinity levels EC in dS/m | | | | | | Year 1988 | Year 1882 |
| | <1 | 1-2 | 2-3 | 3-4 | >4 | | | |
| Eastern Delta | 949 | 1565 | 1055 | 310 | 433 | 4312 | 1130 | 2000 |
| Middle Delta | 330 | 1421 | 1832 | 273 | 1191 | 5047 | 686 | 1400 |
| Western Delta | 473 | 412 | 1291 | 901 | 1914 | 4991 | 554 | 1050 |
| Total | 1752 | 3398 | 4178 | 1484 | 3538 | 14350 | 2370 | 4450 |

In fact, direct use of drainage water for irrigation with salinity varying from 2 to 3 dS/m, is common in the districts of Northern Delta where there are no other alternatives or in areas of limited better water quality supply. Farmers in Beheira, Kafr-El-Sheikh, Damietta and Dakhlia Governorates have successfully used drainage water directly for periods of 25 years to irrigate over 10 000 ha of land, using traditional farming practices. The soil texture ranges from sand, silt loam to clay with calcium carbonate content of 2 to 20 percent and very low in organic matter. The major crops include clover "Berseem", rice, wheat, barley, sugarbeet and cotton. Yield reductions of 25 to 30 percent are apparently acceptable to local farmers. Yield reductions observed are attributed to waterlogging and salinization resulting from over-irrigation and other forms of poor agricultural, soil and water management.

Pilot studies carried out in Kafr el Sheik and Beheira Governorates showed that by applying appropriate management practices (i.e. crop selection, use of soil amendments, deep ploughing, tillage for seedbed preparation, land levelling, fertilization, minimum leaching requirements, mulching and organic manuring), drainage water of salinity 2 to 2.5 dS/m can be safely used for irrigation without long term hazardous consequences to crops or soils (see Table 10).

TABLE 10
**Yields of dominant crops in Kafr el Sheikh and Beheira Governorates using drainage water for irrigation**
(after Mashali 1985)

| Irrigation water | Average yields | | | | |
|---|---|---|---|---|---|
| | Rice<br>tons/ha | Clover (berseem)<br>tons/ha | Barley<br>tons/ha | Cotton<br>tons/ha | Squash<br>kg/ha |
| Drainage Water Kafr El Sheikh (EC = 2-2.5 dS/m) | 8.0 | 150 | - | - | - |
| Drainage water Beheira | 8.2 | 155 | 3.7 | 1.9 | 330 |
| Fresh Nile water (EC = 0.4 dS/m) | 8.5 | 160 | 3.7 | 2.0 | 350 |

In Fayoum Governorate, the annual average volume of drainage water available amounts to 696 MCM, of which 350 MCM per year are used at present after blending with canal water. Results of pilot demonstrations in Ibshwai District during the period 1985 to 1987 on direct and cyclic use of drainage water (EC = 2.8 dS/m) with fresh Nile water are presented in Table 11.

TABLE 11
**Effect of irrigation with different salinity levels on principal crops grown in the area**
(adapted by Mashali based on data reported by Rady 1990)

| Source of irrigation water (EC in dS/m) | Wheat Grain dry tons/ha | Onion tons/ha | Maize tons/ha | Summer tomato tons/ha | Winter tomato tons/ha | Pepper tons/ha |
|---|---|---|---|---|---|---|
| Drainage water (2.8 dS/m with SAR 22) | 5.0 | 6.5 | 1.8 | 2.5 | 8.0 | 12.5 |
| Fresh Nile water for seedling establishment and then drainage water | 3.0 | 6.5 | 2.0 | 4.0 | 8.7 | 20.0 |
| Fresh Nile water (0.5 dS/m with SAR 4) | 5.0 | 9.7 | 2.5 | 7.5 | 12.5 | 25.0 |

The following strategy emerges from these demonstrations, i.e. to irrigate sensitive crops (maize, pepper, onion, alfalfa, etc.) in the rotation with fresh Nile water and salt tolerant crops (wheat, cotton, sugarbeet, etc.) directly with drainage water, and moderately sensitive crops (tomato, lettuce, potato, sunflower, etc.) can be irrigated with drainage water but after seedling establishment with fresh Nile water. Based on these results, the Governorate is planning to reclaim 4000 ha using the drainage water.

The estimated present annual abstraction from groundwater resources in the Nile Valley and Delta is about 2.6 BCM (for agricultural, municipal and industrial use) with an average salinity of 1.5 dS/m but ranging far higher, at least to 4.0 dS/m (the estimated use of this groundwater resource by the year 2010 is 4.9 BCM). Saline groundwaters ranging 2.0 to 4.0 dS/m have been successfully used for decades to irrigate a variety of crops in large areas of scattered farms in the Nile Valley and Delta. Crops now grown are mostly forage, cereals

# Chapter 4

# Water quality assessment

In this chapter methods, criteria and standards for assessing the suitability of saline waters for crop production are discussed, along with concerns and limitations of using saline waters for irrigation.

## CONCERNS AND LIMITATIONS

Salts exert both general and specific effects on plants which directly influence crop yield. Additionally, salts affect certain soil physico-chemical properties which, in turn, may affect the suitability of the soil as a medium for plant growth. The development of appropriate criteria and standards for judging the suitability of a saline water for irrigation and for selecting appropriate salinity control practices requires relevant knowledge of how salts affect soils and plants. This section presents a brief summary of the principal salinity effects that should be thoroughly understood in this regard.

### Effects of Salts on Soils

The suitability of soils for cropping depends heavily on the readiness with which they conduct water and air (permeability) and on aggregate properties which control the friability of the seedbed (tilth). Poor permeability and tilth are often major problems in irrigated lands. Contrary to saline soils, sodic soils may have greatly reduced permeability and poorer tilth. This comes about because of certain physico-chemical reactions associated, in large part, with the colloidal fraction of soils which are primarily manifested in the slaking of aggregates and in the swelling and dispersion of clay minerals.

To understand how the poor physical properties of sodic soils are developed, one must look to the binding mechanisms involving the negatively charged colloidal clays and organic matter of the soil and the associated envelope of electrostatically adsorbed cations around the colloids, and to the means by which exchangeable sodium, electrolyte concentration and pH affect this association. The cations in the "envelope" are subject to two opposing processes:

- they are attracted to the negatively-charged clay and organic matter surfaces by electrostatic forces, and
- they tend to diffuse away from these surfaces, where their concentration is higher, into the bulk of the solution, where their concentration is generally lower.

The two opposing processes result in an approximately exponential decrease in cation concentration with distance from the clay surfaces into the bulk solution. Divalent cations, like calcium and magnesium, are attracted by the negatively-charged surfaces with a force twice as great as monovalent cations like sodium. Thus, the cation envelope in the divalent system is more compressed toward the particle surfaces. The envelope is also compressed by an increase in the electrolyte concentration of the bulk solution, since the tendency of the cations to diffuse away from the surfaces is reduced as the concentration gradient is reduced.

The associations of individual clay particles and organic matter micelles with themselves, each other and with other soil particles to form assemblages called aggregates are diminished when the cation "envelope" is expanded (with reference to the surface of the particle) and are enhanced when it is compressed. The like-electrostatic charges of the particles which repel one another and the opposite-electrostatic charges which attract one another are relatively long-range in effect. On the other hand, the adhesive forces, called Vanderwaal forces, and chemical bonding reactions involved in the particle-to-particle associations which bind such units into assemblages, are relatively short-range forces. The greater the compression of the cation "envelope" toward the particle surface, the smaller the overlap of the "envelopes" and the repulsion between adjacent particles for a given distance between them. Consequently, the particles can approach one another closely enough to permit the adhesive forces to dominate and assemblages (aggregates) to form.

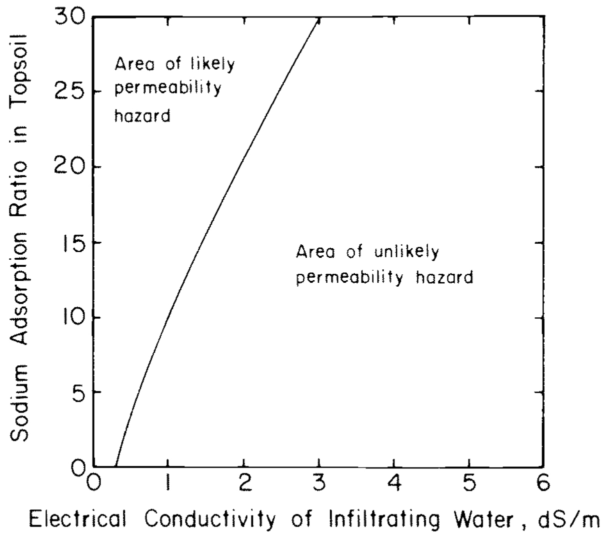
The phenomenon of repulsion between particles causes more soil solution to be imbibed between them (this is called swelling). Because clay particles are plate-like in shape and tend to be arranged in parallel orientation with respect to one another, swelling reduces the size of the inter-aggregate pore spaces in the soil and, hence, permeability. Swelling is primarily important in soils which contain substantial amounts of expanding-layer phyllosilicate clay minerals (smectites like montmorillonite) and which have ESP values in excess of about 15. The reason for this is that, in such minerals, the sodium ions in the pore fluid are first attracted to the external surfaces of the clay plate. Only after satisfying this do the sodium ions occupy the space between the parallel platelets of the oriented and associated clay particles of the sub-aggregates (called domains) where they create the repulsion forces between adjacent platelets which lead to swelling.

Dispersion (release of individual clay platelets from aggregates) and slaking (breakdown of aggregates into subaggregate assemblages) can occur at relatively low ESP values ($< 15$), provided the electrolyte concentration is sufficiently low. The packing of aggregates is more porous than that of individual particles or subaggregates, hence permeability and tilth are better in aggregated conditions. Repulsed clay platelets or slaked subaggregate assembles can lodge in pore interstices, also reducing permeability.

Thus, soil solutions composed of high solute concentrations (salinity), or dominated by calcium and magnesium salts, are conducive to good soil physical properties. Conversely, low salt concentrations and relatively high proportions of sodium salts adversely affect permeability and tilth. High pH ($> 8$) also adversely affects permeability and tilth because it enhances the negative charge of soil clay and organic matter and, hence, the repulsive forces between them.

During an infiltration event, the soil solution of the topsoil is essentially that of the infiltrating water and the exchangeable sodium percentage is essentially that pre-existent in the soil (since ESP is buffered against rapid change by the soil cation exchange capacity). Because all water entering the soil must pass through the soil surface, which is most subject to loss of aggregation, topsoil properties largely control the water entry rate of the soil. These observations taken together with knowledge of the effects of the processes discussed above explain why soil permeability and tilth problems must be assessed in terms of both the salinity of the infiltrating water and the exchangeable sodium percentage (or its equivalent SAR value) and the pH of the topsoil. Representative threshold values of SAR (~ ESP) and the electrical conductivity of infiltrating water for maintenance of soil permeability are given in Figure 2. Because there are significant differences among soils in their susceptibilities in this regard, this relation should only be used as a guideline. The data available on the effect of pH are not yet extensive enough to develop the third axis relation needed to refine this guideline (Suarez *et al.* 1984; Goldberg and Forster 1990; Goldberg *et al.* 1990).

FIGURE 2
**Threshold values of SAR of topsoil and EC of infiltrating water for maintenance of soil permeability (after Rhoades 1982)**



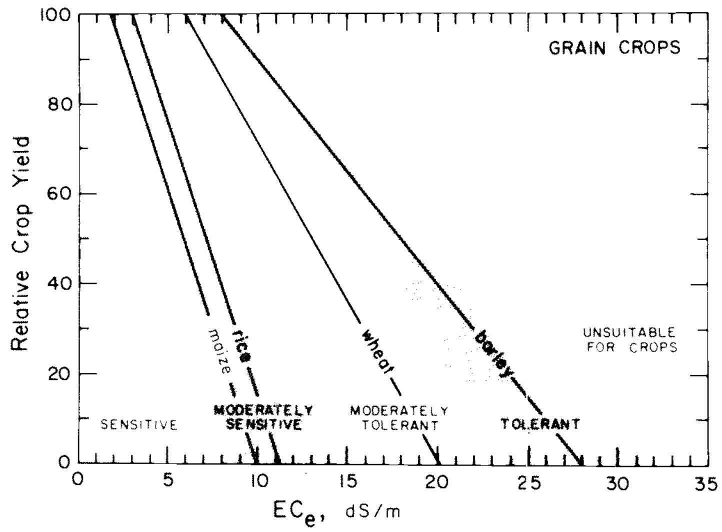

Decreases in the infiltration rate (IR) of a soil generally occur over the irrigation season because of the gradual deterioration of the soil's structure and the formation of a surface seal (horizontally layered arrangement of discrete soil particles) created during successive irrigations (sedimentation, wetting and drying events). IR is even more sensitive to exchangeable sodium, electrolyte concentration and pH than is hydraulic conductivity. This is due to the increased vulnerability of the topsoil to mechanical forces, which enhance clay dispersion, aggregate slaking and the movement of clay in the "loose" near-surface soil, and to the lower electrolyte concentration that generally exists there, especially under conditions of rainfall. Depositional crusts often form in the furrows of irrigated soils where soil particles suspended in water are deposited as the water flow rate slows or the water infiltrates. The hydraulic conductivity of such crusts is often two to three orders of magnitude lower than that of the underlying bulk soil, especially when the electrolyte concentration of the infiltrating water is low and exchangeable sodium is relatively high.

The addition of gypsum (either to the soil or water) can often help appreciably in avoiding or alleviating problems of reduced infiltration rate and hydraulic conductivity. For more specific information on the effects of exchangeable sodium, electrolyte concentration and pH, as well as of exchangeable Mg and K, and use of amendments on the permeability and infiltration rate of soils reference should be made to the reviews of Keren and Shainberg (1984); Shainberg (1984); Emerson (1984); Shainberg and Letey (1984); Shainberg and Singer (1990).

## Effects of Salts on Plants

Excess salinity within the plant rootzone has a general deleterious effect on plant growth which is manifested as nearly equivalent reductions in the transpiration and growth rates

FIGURE 3
**Salt tolerance of grain crops (after Maas and Hoffman 1977)**




(including cell enlargement and the synthesis of metabolites and structural compounds). This effect is primarily related to total electrolyte concentration and is largely independent of specific solute composition. The hypothesis that best seems to fit observations is that excessive salinity reduces plant growth primarily because it increases the energy that must be expended to acquire water from the soil of the rootzone and to make the biochemical adjustments necessary to survive under stress. This energy is diverted from the processes which lead to growth and yield.

Growth suppression is typically initiated at some threshold value of salinity, which varies with crop tolerance and external environmental factors which influence the need of the plant for water, especially the evaporative demand of the atmosphere (temperature, relative humidity, windspeed, etc.) and the water-supplying potential of the rootzone, and increases as salinity increases until the plant dies. The salt tolerances of various crops are conventionally expressed (after Maas and Hoffman 1977), in terms of relative yield ($Y_r$), threshold salinity value (a), and percentage decrement value per unit increase of salinity in excess of the threshold (b); where soil salinity is expressed in terms of $EC_e$, in dS/m), as follows:

$$Y_r = 100 - b\,(EC_e - a) \tag{1}$$

where $Y_r$ is the percentage of the yield of the crop grown under saline conditions relative to that obtained under non-saline, but otherwise comparable, conditions. This use of $EC_e$ to express the effect of salinity on yield implies that crops respond primarily to the osmotic potential of the soil solution. Tolerances to specific ions or elements are considered separately, where appropriate.

Some representative salinity tolerances of grain crops are given in Figure 3 to illustrate the conventional manner of expressing crop salt tolerance. Compilations of data on crop tolerances to salinity and some specific ions and elements are given in Tables 12 to 21 (after Maas 1986; 1990).

TABLE 12
**Relative salt tolerance of various crops at emergence and during growth to maturity**
(after Maas 1986)

| Crop | | Electrical conductivity of saturated soil extract | |
|---|---|---|---|
| Common name | Botanical name[1] | 50% yield dS/m | 50% emergence[2] dS/m |
| Barley | *Hordeum vulgare* | 18 | 16-24 |
| Cotton | *Gossypium hirsutum* | 17 | 15 |
| Sugarbeet | *Beta vulgaris* | 15 | 6-12 |
| Sorghum | *Sorghum bicolor* | 15 | 13 |
| Safflower | *Carthamus tinctorius* | 14 | 12 |
| Wheat | *Triticum aestivum* | 13 | 14-16 |
| Beet, red | *Beta vulgaris* | 9.6 | 13.8 |
| Cowpea | *Vigna unguiculata* | 9.1 | 16 |
| Alfalfa | *Medicago sativa* | 8.9 | 8-13 |
| Tomato | *Lycopersicon lycopersicum* | 7.6 | 7.6 |
| Cabbage | *Brassica oleracea capitata* | 7.0 | 13 |
| Maize | *Zea mays* | 5.9 | 21-24 |
| Lettuce | *Lactuca sativa* | 5.2 | 11 |
| Onion | *Allium cepa* | 4.3 | 5.6-7.5 |
| Rice | *Oryza sativa* | 3.6 | 18 |
| Bean | *Phaseolus vulgaris* | 3.6 | 8.0 |

1 Botanical and common names follow the convention of Hortus Third where possible.
2 Emergence percentage of saline treatments determined when non-saline treatments attained maximum emergence.

It is important to recognize that such salt tolerance data cannot provide accurate, quantitative crop yield losses from salinity for every situation, since actual response to salinity varies with other conditions of growth including climatic and soil conditions, agronomic and irrigation management, crop variety, stage of growth, etc. While the values are not exact, since they incorporate interactions between salinity and the other factors, they can be used to predict how one crop might fare relative to another under saline conditions.

Climate is a major factor affecting salt tolerance; most crops can tolerate greater salt stress if the weather is cool and humid than if it is hot and dry. Yield is reduced more by salinity when atmospheric humidity is low. Ozone decreases the yield of crops more under non-saline than saline conditions, thus the effects of ozone and humidity increase the apparent salt tolerance of certain crops.

Plants are generally relatively tolerant during germination (see Table 12) but become more sensitive during emergence and early seedling stages of growth; hence it is imperative to keep salinity in the seedbed low at these times. If salinity levels reduce plant stand (as it commonly does), potential yields will be decreased far more than that predicted by the salt tolerance data given in Tables 13-15, since they apply to growth after seedling establishment.

Significant differences in salt tolerance occur among varieties of some species though this issue is confused because of the different climatic or nutritional conditions under which the crops were tested and the possibility of better varietal adaption in this regard. Rootstocks affect the salt tolerances of tree and vine crops because they affect the ability of the plant to extract soil water and the uptake and translocation to the shoots of the potentially toxic sodium and chloride salts.

TABLE 13
**Salt tolerance of herbaceous crops**[1] (after Maas 1986)

| Crop | | Electrical conductivity of saturated soil extract | | Rating[4] |
|---|---|---|---|---|
| Common name | Botanical name[2] | Threshold[3] dS/m | slope %/ dS/m | |
| **Fibre, grain & special crops** | | | | |
| Barley[5] | *Hordeum vulgare* | 8.0 | 5.0 | T |
| Bean | *Phaseolus vulgaris* | 1.0 | 19.0 | S |
| Broadbean | *Vicia faba* | 1.6 | 9.6 | MS |
| Cotton | *Gossypium hirsutum* | 7.7 | 5.2 | T |
| Cowpea | *Vigna unguiculata* | 4.9 | 12.0 | MT |
| Flax | *Linum usitatissimum* | 1.7 | 12.0 | MS |
| Groundnut | *Arachis hypogaea* | 3.2 | 29.0 | MS |
| Guar | *Cyamopsis tetragonoloba* | 8.8 | 17.0 | T |
| Kenaf | *Hibiscus cannabinus* | | | MT |
| Maize[6] | *Zea mays* | 1.7 | 12.0 | MS |
| Millet, foxtail | *Setaria italica* | | | MS |
| Oats | *Avena sativa* | | | MT* |
| Rice, paddy | *Oryza sativa* | 3.0[7] | 12.0[7] | S |
| Rye | *Secale cereale* | 11.4 | 10.8 | T |
| Safflower | *Carthamus tinctorius* | | | MT |
| Sesame[8] | *Sesamum indicum* | | | S |
| Sorghum | *Sorghum bicolor* | 6.8 | 16.0 | MT |
| Soybean | *Glycine max* | 5.0 | 20.0 | MT |
| Sugarbeet[8] | *Beta vulgaris* | 7.0 | 5.9 | T |
| Sugarcane | *Saccharum officinarum* | 1.7 | 5.9 | MS |
| Sunflower | *Helianthus annuus* | | | MS* |
| Triticale | *X Triticosecale* | 6.1 | 2.5 | T |
| Wheat | *Triticum aestivum* | 6.0 | 7.1 | MT |
| Wheat (semidwarf)[10] | *T. aestivum* | 8.6 | 3.0 | T |
| Wheat, Durum | *T. turgidum* | 5.9 | 3.8 | T |
| **Grasses & forage crops** | | | | |
| Alfalfa | *Medicago sativa* | 2.0 | 7.3 | MS |
| Alkaligrass, Nuttall | *Puccinellia airoides* | | | T* |
| Alkali sacaton | *Sporobolus airoides* | | | T* |
| Barley (forage)[5] | *Hordeum vulgare* | 6.0 | 7.1 | MT |
| Bentgrass | *A. stolonifera palustris* | | | MS |
| Bermudagrass[11] | *Cynodon dactylon* | 6.9 | 6.4 | T |
| Bluestem, Angleton | *Dichanthium aristatum* | | | MS* |
| Brome, mountain | *Bromus marginatus* | | | MT* |
| Brome, smooth | *B. inermis* | | | MS |
| Buffelgrass | *Cenchrus ciliaris* | | | MS* |
| Burnet | *Poterium sanguisorba* | | | MS* |
| Canarygrass, reed | *Phalaris arundinacea* | | | MT |
| Clover, alsike | *Trifolium hybridium* | 1.5 | 12.0 | MS |
| Clover, Berseem | *T. alexandrinum* | 1.5 | 5.7 | MS |
| Clover, Hubam | *Melilotus alba* | | | MT* |
| Clover, ladino | *Trifolium repens* | 1.5 | 12.0 | MS |
| Clover, red | *T. pratense* | 1.5 | 12.0 | MS |
| Clover, strawberry | *T. fragiferum* | 1.5 | 12.0 | MS |
| Clover sweet | *Melilotus* | | | MT* |
| Clover, white Dutch | *Trifolium repens* | | | MS* |
| Cowpea (forage) | *Vigna unguiculata* | 2.5 | 11.0 | MS |
| Dallisgrass | *Paspalum dilatatum* | | | MS* |
| Fescue, tall | *Festuca elatior* | 3.9 | 5.3 | MT |
| Fescue, meadow | *F. pratensis* | | | MT* |

TABLE 13 Cont'd

| Crop | | Electrical conductivity of saturated soil extract | | Rating[4] |
|---|---|---|---|---|
| Common name | Botanical name[2] | Threshold[3] dS/m | slope %/ dS/m | |
| Foxtail, meadow | *Alopecurus pratensis* | 1.5 | 9.6 | MS |
| Grama, blue | *Bouteloua gracilis* | | | MS* |
| Hardinggrass | *Phalaris tuberosa* | 4.6 | 7.6 | MT |
| Kallargrass | *Diplachne fusca* | | | T* |
| Lovegrass[12] | *Eragrostis* sp. | 2.0 | 8.4 | MS |
| Maize (forage)[6] | *Zea mays* | 1.8 | 7.4 | MS |
| Milkvetch, Cicer | *Astragalus cicer* | | | MS* |
| Oatgrass, tall | *Arrhenatherum, Danthonia* | | | MS* |
| Oats (forage) | *Avena sativa* | | | MS* |
| Orchardgrass | *Dactylis glomerata* | 1.5 | 6.2 | MS |
| Panicgrass, blue | *Panicum antidotale* | | | MT* |
| Rape | *Brassica napus* | | | MT* |
| Rescuegrass, blue | *Bromus unioloides* | | | MT* |
| Rhodesgrass | *Chloris gayana* | | | MT |
| Rey (forage) | *Secale cereale* | | | MS* |
| Ryegrass, Italian | *Lolium italicum multiflorum* | | | MT* |
| Ryegrass, perennial | *L. perenne* | 5.6 | 7.6 | MT |
| Saltgrass, desert | *Distichlis stricta* | | | T* |
| Sesbania | *Sesbania exaltata* | 2.3 | 7.0 | MS |
| Sirato | *Macroptilium atropurpureum* | | | MS |
| Sphaerophysa | *Sphaerophysa salsula* | 2.2 | 7.0 | MS |
| Sudangrass | *Sorghum sudanense* | 2.8 | 4.3 | MT |
| Timothy | *Phleum pratense* | | | MS* |
| Trefoil, big | *Lotus uliginosus* | 2.3 | 19.0 | MS |
| Trefoil, narrowleaf birdsfoot | *L. corniculatus tenuifolium* | 5.0 | 10.0 | MT |
| Trefoil, broadleaf birdsfoot[13] | *L. corniculatus arvenis* | | | MT |
| Vetch, common | *Vicia angustifolia* | 3.0 | 11.0 | MS |
| Wheat (forage)[10] | *Triticum aestivum* | 4.5 | 2.6 | MT |
| Wheat, Durum (forage) | *T. turgidum* | 2.1 | 2.5 | MT |
| Wheatgrass, stand. crested | *Agropyron sibiricum* | 3.5 | 4.0 | MT |
| Wheatgrass, fairway crested | *A. cristatum* | 7.5 | 6.9 | T |
| Wheatgrass, intermediate | *A. intermedium* | | | MT* |
| Wheatgrass, slender | *A. trachycaulum* | | | MT |
| Wheatgrass, tall | *A. elongatum* | 7.5 | 4.2 | T |
| Wheatgrass, western | *A. smithii* | | | MT* |
| Wildrye, Altai | *Elymus angustus* | | | T |
| Wildrye, beardless | *E. triticoides* | 2.7 | 6.0 | MT |
| Wildrye, Canadian | *E. canadensis* | | | MT* |
| Wildrye, Russian | *E. junceus* | | | T |
| **Vegetables & fruit crops** | | | | |
| Artichoke | *Helianthus tuberosus* | | | MT* |
| Asparagus | *Asparagus officinalis* | 4.1 | 2.0 | T |
| Bean | *Phaseolus vulgaris* | 1.0 | 19.0 | S |
| Beet, red[8] | *Beta vulgaris* | 4.0 | 9.0 | MT |
| Broccoli | *Brassica oleracea botrytis* | 2.8 | 9.2 | MS |
| Brussel sprouts | *B. oleracea gemmifera* | 1.8 | 9.7 | MS* |
| Cabbage | *B. oleracea capitata* | 1.0 | 14.0 | MS |
| Carrot | *Daucus carota* | | | S |
| Cauliflower | *Brassica oleracea botrytis* | 1.8 | 6.2 | MS* |
| Celery | *Apium graveolens* | 2.5 | 13.0 | MS |

TABLE 13 Cont'd

| Crop | | Electrical conductivity of saturated soil extract | | Rating[4] |
|---|---|---|---|---|
| Common name | Botanical name[2] | Threshold[3] dS/m | slope %/ dS/m | |
| Cucumber | *Cucumis sativus* | 1.1 | 6.9 | MS |
| Eggplant | *Solanum melongena esculentum* | | | MS |
| Kale | *Brassica oleracea acephala* | | | MS* |
| Kohlrabi | *B. oleracea gongylode* | 1.3 | 13.0 | MS* |
| Lettuce | *Lactuca sativa* | 1.7 | 12.0 | MS |
| Maize, sweet | *Zea mays* | | | MS |
| Muskmelon | *Cucumis melo* | | | MS |
| Okra | *Abelmoschus esculentus* | 1.2 | 16.0 | S |
| Onion | *Allium cepa* | | | S |
| Parsnip | *Pastinaca sativa* | | | S* |
| Pea | *Pisum sativum* | 1.5 | 14.0 | S* |
| Pepper | *Capsicum annuum* | 1.7 | 12.0 | MS |
| Potato | *Solanum tuberosum* | | | MS |
| Pumpkin | *Cucurbita pepo pepo* | 1.2 | 13.0 | MS* |
| Radish | *Raphanus sativus* | 2.0 | 7.6 | MS |
| Spinach | *Spinacia oleracea* | 3.2 | 16.0 | MS |
| Squash, scallop | *Cucurbita pepo melopepo* | 4.7 | 9.4 | MS |
| Squash, zucchini | *C. pepo melopepo* | 1 | 33 | MT |
| Strawberry | *Fragaria* sp. | 1.5 | 11 | S |
| Sweet potato | *Ipomoea batatas* | 2.5 | 9.9 | MS |
| Tomato | *Lycopersicon lycopersicum* | 0.9 | 9 | MS |
| Turnip | *Brassica rapa* | | | MS |
| Watermelon | *Citrullus lanatus* | | | MS* |

1 These data serve only as a guideline to relative tolerances among crops. Absolute tolerances vary, depending upon climate, soil conditions and cultural practices.

2 Botanical and common names follow the convention of Hortus Third where possible.

3 In gypsiferous soils, plants will tolerate $EC_e$s about 2 dS/m higher than indicated.

4 T = Tolerant, MT = Moderately Tolerant, MS = Moderately Sensitive and S = Sensitive. Ratings with an * are estimates.

5 Less tolerant during seedling stage, $EC_e$ at this stage should not exceed 4 or 5 dS/m.

6 Grain and forage yields of DeKalb XL-75 grown on an organic muck soil decreased about 26% per dS/m above a threshold of 1.9 dS/m.

7 Because paddy rice is grown under flooded conditions, values refer to the electrical conductivity of the soil water while the plants are submerged. Less tolerant during seedling stage.

8 Sesame cultivars, Sesaco 7 and 8, may be more tolerant than indicated by the S rating.

9 Sensitive during germination and emergence, $EC_e$ should not exceed 3 dS/m.

10 Data from one cultivar, "Probred".

11 Average of several varieties. Suwannee and Coastal are about 20% more tolerant, and common and Greenfield are about 20% less tolerant than the average.

12 Average for Boer, Wilman, Sand and Weeping cultavars. Lehmann seems about 50% more tolerant.

13 Broadleaf birdsfoot trefoil seems less tolerant than narrowleaf.

TABLE 14
**Salt tolerance of woody crops**[1] (after Maas 1986)

| Crop | | Electrical conductivity of saturated soil extract | | Rating[4] |
|---|---|---|---|---|
| Common name | Botanical name[2] | Threshold[3] dS/m | slope %/dS/m | |
| Almond[5] | *Prunus duclis* | 1.5 | 19.0 | S |
| Apple | *Malus sylvestris* | | | S |
| Apricot[5] | *Prunus armeniaca* | 1.6 | 24.0 | S |
| Avocado[5] | *Persea americana* | | | S |
| Blackberry | *Rubus* sp. | 1.5 | 22.0 | S |
| Boysenberry | *Rubus ursinus* | 1.5 | 22.0 | S |
| Castorbean | *Ricinus communis* | | | MS* |
| Cherimoya | *Annona cherimola* | | | S* |
| Cherry, sweet | *Prunus avium* | | | S* |
| Cherry, sand | *P. besseyi* | | | S* |
| Currant | *Ribes* sp. | | | S* |
| Date palm | *Phoenix dactylifera* | 4.0 | 3.6 | T |
| Fig | *Ficus carica* | | | MT* |
| Gooseberry | *Ribes* sp. | | | S* |
| Grape[5] | *Vitis* sp. | 1.5 | 9.6 | MS |
| Grapefruit[5] | *Citrus paradisi* | 1.8 | 16.0 | S |
| Guayule | *Parthenium argentatum* | 15.0 | 13.0 | T |
| Jojoba[5] | *Simmondsia chinensis* | | | T |
| Jujube | *Ziziphus jujuba* | | | MT* |
| Lemon[5] | *Citrus limon* | | | S |
| Lime | *C. aurantiifolia* | | | S* |
| Loquat | *Eriobotrya japonica* | | | S* |
| Mango | *Mangifera indica* | | | S* |
| Olive | *Olea europaea* | | | MT |
| Orange | *Citrus sinensis* | 1.7 | 16.0 | S |
| Papaya[5] | *Carica papaya* | | | MT |
| Passion fruit | *Passiflora edulis* | | | S* |
| Peach | *Prunus persica* | 1.7 | 21.0 | S |
| Pear | *Pyrus communis* | | | S* |
| Persimmon | *Diospyros virginiana* | | | S* |
| Pineapple | *Ananas comosus* | | | MT* |
| Plum; prune[5] | *Prunus domestica* | 1.5 | 18.0 | S |
| Pomegranate | *Punica granatum* | | | MT* |
| Pummelo | *Citrus maxima* | | | S* |
| Raspberry | *Rubus idaeus* | | | S |
| Rose apple | *Syzygium jambos* | | | S* |
| Sapote, white | *Casimiroa edulis* | | | S* |
| Tangerine | *Citrus reticulata* | | | S* |

1 These data are applicable when rootstocks are used that do not accumulate $Na^+$ or $Cl^-$ rapidly or when these ions do not predominate in the soil.

2 Botanical and common names follow the convention of Hortus Third where possible.

3 In gypsiferous soils, plants will tolerate $EC_e$s about 2 dS/m higher than indicated.

4 T = Tolerant, MT = Moderately Tolerant, MS = Moderately Sensitive and S = Sensitive. Ratings with an * are estimates.

5 Tolerance is based on growth rather than yield.

Table 15
**Salt tolerance of ornamental shrubs, trees and ground cover**[1]
(after Maas 1986)

| Common name | Botanical name | Maximum permissible[2] $EC_e$ dS/m |
|---|---|---|
| **Very sensitive** | | |
| Star jasmine | *Trachelospermum jasminoides* | 1-2 |
| Pyrenees cotoneaster | *Cotoneaster congestus* | 1-2 |
| Oregon grape | *Mahonia aquifolium* | 1-2 |
| Photinia | *Photinia x fraseri* | 1-2 |
| **Sensitive** | | |
| Pineapple guava | *Feijoa sellowiana* | 2-3 |
| Chinese holly, cv. Burford | *Ilex cornuta* | 2-3 |
| Rose, cv. Grenoble | *Rosa sp.* | 2-3 |
| Glossy abelia | *Abelia x grandiflora* | 2-3 |
| Southern yew | *Podocarpus macrophyllus* | 2-3 |
| Tulip tree | *Liriodendron tulipifera* | 2-3 |
| Algerian ivy | *Hedera canariensis* | 3-4 |
| Japanese pittosporum | *Pittosporum tobira* | 3-4 |
| Heavenly bamboo | *Nandina domestica* | 3-4 |
| Chinese hibiscus | *Hibiscus rosa-sinensis* | 3-4 |
| Laurustinus, cv. Robustum | *Viburnum tinusm* | 3-4 |
| Strawberry tree, cv. Compact | *Arbutus unedo* | 3-4 |
| Crape Myrtle | *Lagerstroemia indica* | 3-4 |
| **Moderately sensitive** | | |
| Glossy privet | *Ligustrum lucidum* | 4-6 |
| Yellow sage | *Lantana camara* | 4-6 |
| Orchid tree | *Bauhinia purpurea* | 4-6 |
| Southern Magnolia | *Magnolia grandiflora* | 4-6 |
| Japanese boxwood | *Buxus microphylla var. japonica* | 4-6 |
| Xylosma | *Xylosma congestum* | 4-6 |
| Japanese black pine | *Pinus thunbergiana* | 4-6 |
| Indian hawthorn | *Raphiolepis indica* | 4-6 |
| Dodonaea, cv. atropurpurea | *Dodonaea viscosa* | 4-6 |
| Oriental arborvitae | *Platycladus orientalis* | 4-6 |
| Thorny elaeagnus | *Elaeagnus pungens* | 4-6 |
| Spreading juniper | *Juniperus chinensis* | 4-6 |
| Pyracantha, cv. Graberi | *Pyracantha fortuneana* | 4-6 |
| Cherry plum | *Prunus cerasifera* | 4-6 |
| **Moderately tolerant** | | |
| Weeping bottlebruch | *Callistemon viminalis* | 6-8 |
| Oleander | *Nerium oleander* | 6-8 |
| European fan palm | *Chamaerops humilis* | 6-8 |
| Blue dracaena | *Cordyline indivisa* | 6-8 |
| Spindle tree, cv. Grandiflora | *Euonymus japonica* | 6-8 |
| Rosemary | *Rosmarinus officinalis* | 6-8 |
| Aleppo pine | *Pinus halepensis* | 6-8 |
| Sweet gum | *Liquidamabar styraciflua* | 6-8 |
| **Tolerant** | | |
| Brush cherry | *Syzygium paniculatum* | >8[3] |
| Ceniza | *Leucophyllum frutescens* | >8[3] |
| Natal palm | *Carissa grandiflora* | >8[3] |
| Evergreen pear | *Pyrus kawakamii* | >8[3] |
| Bougainvillea | *Bougainvillea spectabilis* | >8[3] |
| Italian stone pine | *Pinus pinea* | >8[3] |

| Common name | Botanical name | Maximum permissible[2] $EC_e$ dS/m |
|---|---|---|
| **Very tolerant** | | |
| White iceplant | *Delosperma alba* | >10[3] |
| Rosea iceplant | *Drosanthemum hispidum* | >10[3] |
| Purple iceplant | *Lampranthus productus* | >10[3] |
| Croceum iceplant | *Hymenocyclus croceus* | >10[3] |

[1] Species are listed in order of increasing tolerance based on appearance as well as growth reduction.

[2] Salinities exceeding the maximum permissible $EC_e$ may cause leaf burn, loss of leaves, and/or excessive stunting.

[3] Maximum permissible $EC_e$ is unknown. No injury symptoms or growth reduction was apparent at 7 dS/m. The growth of all iceplant species was increased by soil salinity of 7 dS/m.

Salt tolerance also depends somewhat upon the type, method and frequency of irrigation. As the soil dries, plants experience matric stresses, as well as osmotic stresses, which also limit water uptake. The prevalent salt tolerance data apply most directly to crops irrigated by surface (furrow and flood) methods and conventional irrigation management. Salt concentrations may differ several-fold within irrigated soil profiles and they change constantly. The plant is most responsive to salinity in that part of the rootzone where most of the water uptake occurs. Therefore, ideally, tolerance should be related to salinity weighted over time and measured where the roots absorb most of the water.

Sprinkler-irrigated crops are potentially subject to additional damage caused by foliar salt uptake and desiccation (burn) from spray contact of the foliage. For example, Bernstein and Francois (1973a) found that the yields of bell peppers were reduced by 59 percent more when 4.4 dS/m water was applied by sprinklers compared to a drip system. Meiri (1984) found similar results for potatoes. The information base available to predict yield losses from foliar spray effects of sprinkler irrigation is quite limited, though some data are given in Table 16. Susceptibility of plants to foliar salt injury depends on leaf characteristics affecting rate of absorption and is not generally correlated with tolerance to soil salinity. The degree of spray injury varies with weather conditions, especially the water deficit of the atmosphere. Visible symptoms may appear suddenly following irrigations when the weather is hot and dry. Increased frequency of sprinkling, in addition to increased temperature and evaporation, leads to increases in salt concentration in the leaves and in foliar damage.

While the primary effect of soil salinity on herbaceous crops is one of retarding growth, as discussed above, certain salt constituents are specifically toxic to some crops. Boron is such a solute and, when present in the soil solution at concentrations of only a few mg/l, is highly toxic to susceptible crops. Boron toxicities may also be described in terms of a threshold value and yield-decrement slope parameters, as is salinity. Available summaries are given in Tables 17 to 19. For some crops, especially woody perennials, sodium and chloride may accumulate in the tissue over time to toxic levels that produce foliar burn. Generally these plants are also salt-sensitive and the two effects are difficult to separate. Chloride tolerance levels for crops are given in Tables 20 and 21.

Sodic soil conditions may induce calcium, as well as other nutrient, deficiencies because the associated high pH and bicarbonate conditions repress the solubilities of many soil minerals, hence limiting nutrient concentrations in solution and, thus, availability to the plant.

TABLE 16

**Relative susceptibility of crops to foliar injury from saline sprinkling water**[1] (after Maas 1990)

| Na or Cl conc ($mmol_c/l$) causing foliar injury[2] | | | |
|---|---|---|---|
| < 5 | 5-10 | 10-20 | > 20 |
| Almond<br>Apricot<br>Citrus<br>Plum | Grape<br>Pepper<br>Potato<br>Tomato | Alfalfa<br>Barley<br>Cucumber<br>Maize<br>Safflower<br>Sesame<br>Sorghum | Cauliflower<br>Cotton<br>Sugarbeet<br>Sunflower |

1 Susceptibility based on direct accumulation of salts through the leaves.
2 Foliar injury is influenced by cultural and environmental conditions. These data are presented only as general guidelines for day-time sprinkling.

TABLE 17

**Boron tolerance limits for agricultural crops** (after Maas 1990)

| Common name | Botanical name | Threshold[1] $g/m^3$ | Slope % per $g/m^3$ |
|---|---|---|---|
| **Very sensitive** | | | |
| Lemon[2] | *Citrus limon* | < 0.5 | |
| Blackberry[2] | *Rubus* sp. | < 0.5 | |
| **Sensitive** | | | |
| Avocado[2] | *Persea americana* | 0.5-7.5 | |
| Grapefruit[2] | *C. x paradisi* | 0.5-7.5 | |
| Orange[2] | *C. sinensis* | 0.5-7.5 | |
| Apricot[2] | *Prunus armeniaca* | 0.5-7.5 | |
| Peach[2] | *P. persica* | 0.5-7.5 | |
| Cherry[2] | *P. avium* | 0.5-7.5 | |
| Plum[2] | *P. domestica* | 0.5-7.5 | |
| Persimmon[2] | *Diospyros kaki* | 0.5-7.5 | |
| Fig, kadota[2] | *Ficus carica* | 0.5-7.5 | |
| Grape[2] | *Vitis vinifera* | 0.5-7.5 | |
| Walnut[2] | *Juglans regia* | 0.5-7.5 | |
| Pecan[2] | *Carya illinoiensis* | 0.5-7.5 | |
| Onion | *Allium cepa* | 0.5-7.5 | |
| Garlic | *A. sativum* | 0.75-1.0 | |
| Sweet potato | *Ipomoea batatas* | 0.75-1.0 | |
| Wheat | *Triticum aestivum* | 0.75-1.0 | 3.3 |
| Sunflower | *Helianthus annuus* | 0.75-1.0 | |
| Bean, mung[2] | *Vigna radiata* | 0.75-1.0 | |
| Sesame[2] | *Sesamum indicum* | 0.75-1.0 | |
| Lupine[2] | *Lupinus hartwegii* | 0.75-1.0 | |
| Strawberry[2] | *Fragaria sp.* | 0.75-1.0 | |
| Artichoke, Jerusalem[2] | *Helianthus tuberosus* | 0.75-1.0 | |
| Bean, kidney[2] | *Phaseolus vulgaris* | 0.75-1.0 | |
| Bean, snap | *P. vulgaris* | 1.0 | 12 |
| Bean, lima[2] | *P. lunatus* | 0.75-1.0 | |
| Groundnut | *Arachis hypogaea* | 0.75-1.0 | |

TABLE 17 Cont'd

| Common name | Botanical name | Threshold[1] g/m$^3$ | Slope % per g/m$^3$ |
|---|---|---|---|
| **Moderately tolerant** | | | |
| Broccoli | *Brassica oleracea botrytis* | 1.0 | 1.8 |
| Pepper, red | *Capsicum annuum* | 1.0-2.0 | |
| Pea[2] | *Pisum sativa* | 1.0-2.0 | |
| Carrot | *Daucus carota* | 1.0-2.0 | |
| Radish | *Raphanus sativus* | 1.0 | 1.4 |
| Potato | *Solanum tuberosum* | 1.0-2.0 | |
| Cucumber | *Cucumis sativus* | 1.0-2.0 | |
| Lettuce | *Lactuca sativa* | 1.3 | 1.7 |
| Cabbage[2] | *Brassica oleracea capitata* | 2.0-4.0 | |
| Turnip | *B. rapa* | 2.0-4.0 | |
| Bluegrass, Kentucky[2] | *Poa pratensis* | 2.0-4.0 | |
| Barley | *Hordeum vulgare* | 3.4 | 4.4 |
| Cowpea | *Vigna unguiculata* | 2.5 | 12 |
| Oats | *Avena sativa* | 2.0-4.0 | |
| Maize | *Zea mays* | 2.0-4.0 | |
| Artichoke[2] | *Cynara scolymus* | 2.0-4.0 | |
| Tobacco[2] | *Nicotiana tabacum* | 2.0-4.0 | |
| Mustard[2] | *Brassica juncea* | 2.0-4.0 | |
| Clover, sweet[2] | *Melilotus indica* | 2.0-4.0 | |
| Squash | *Cucurbita pepo* | 2.0-4.0 | |
| Muskmelon[2] | *Cucumis melo* | 2.0-4.0 | |
| Cauliflower | *B. olearacea botrytis* | 4.0 | 1.9 |
| **Tolerant** | | | |
| Alfalfa[2] | *Medicago sativa* | 4.0-6.0 | |
| Vetch, purple[2] | *Vicia benghalensis* | 4.0-6.0 | |
| Parsley[2] | *Petroselinum crispum* | 4.0-6.0 | |
| Beet, red | *Beta vulgaris* | 4.0-6.0 | |
| Sugarbeet | *B. vulgaris* | 4.9 | 4.1 |
| Tomato | *Lycopersicon lycopersicum* | 5.7 | 3.4 |
| **Very tolerant** | | | |
| Sorghum | *Sorghum bicolor* | 7.4 | 4.7 |
| Cotton | *Gossypium hirsutum* | 6.0-10.0 | |
| Celery[2] | *Apium graveolens* | 9.8 | 3.2 |
| Asparagus[2] | *Asparagus officinalis* | 10.0-15.0 | |

1 Maximum permissible concentration in soil water without yield reduction. Boron tolerances may vary, depending upon climate, soil conditions and crop varieties.

2 Tolerance based on reductions in vegetative growth.

These conditions can be improved through the use of certain amendments such as gypsum and sulphuric acid. Sodic soils are of less extent than saline soils in most irrigated lands. For more information on the diagnosis and amelioration of such soils see Rhoades (1982), Rhoades and Loveday (1990 and Keren and Miyamoto (1990).

Crops grown on fertile soil may seem more salt tolerant than those grown with adequate fertility, because fertility is the primary factor limiting growth. However, the addition of extra fertilizer will not alleviate growth inhibition by salinity.

For a more thorough treatise on the effects of salinity on the physiology and biochemistry of plants, see the reviews of Maas and Nieman (1978), Maas (1990) and Lauchli and Epstein (1990).

TABLE 18
**Boron tolerances for ornamentals**[1] (after Maas 1990)

| Common name | Botanical name | Threshold[2] mg/l |
|---|---|---|
| **Very sensitive** | | |
| Oregon grape | *Mahonia aquifolium* | < 0.5 |
| Photinia | *Photinia x fraseri* | < 0.5 |
| Xylosma | *Xylosma congestum* | < 0.5 |
| Thorny elaeagnus | *Elaeagnus pungens* | < 0.5 |
| Laurustinus | *Viburnum tinus* | < 0.5 |
| Wax-leaf privet | *Ligustrum japonicum* | < 0.5 |
| Pineapple guava | *Feijoa sellowiana* | < 0.5 |
| Spindle tree | *Euonymus japonica* | < 0.5 |
| Japanese pittosporum | *Pittosporum tobira* | < 0.5 |
| Chinese holly | *Ilex cornuta* | < 0.5 |
| Juniper | *Juniperus chinensis* | < 0.5 |
| Yellow sage | *Lantana camara* | < 0.5 |
| American elm | *Ulmus americana* | < 0.5 |
| **Sensitive** | | |
| Zinnia | *Zinnia eleganus* | 0.5-1.0 |
| Pansy | *Viola tricolor* | 0.5-1.0 |
| Violet | *V. odorata* | 0.5-1.0 |
| Larkspur | *Delphinium* sp. | 0.5-1.0 |
| Glossy abelia | *Abelia x grandiflora* | 0.5-1.0 |
| Rosemary | *Rosmarinus officinalis* | 0.5-1.0 |
| Oriental arbovitae | *Platycladus orientalis* | 0.5-1.0 |
| Geranium | *Pelargonium x hortorum* | 0.5-1.0 |
| **Moderately sensitive** | | |
| Gladiolus | *Gladiolus* sp. | 1.0-2.0 |
| Marigold | *Calendula officinalis* | 1.0-2.0 |
| Poinsettia | *Euphorbia pulcherrima* | 1.0-2.0 |
| China aster | *Callistephus chinensis* | 1.0-2.0 |
| Gardenia | *Gardenia* sp. | 1.0-2.0 |
| Southern yew | *Podocarpus marcophyllus* | 1.0-2.0 |
| Brush cherry | *Syzygium paniculatum* | 1.0-2.0 |
| Blue dracaena | *Cordyline indivisa* | 1.0-2.0 |
| Ceniza | *Leucophyllus frutescens* | 1.0-2.0 |
| **Moderately tolerant** | | |
| Bottlebrush | *Callistemon citrinus* | 2.0-4.0 |
| California poppy | *Eschscholzia californica* | 2.0-4.0 |
| Japanese boxwood | *Buxus microphylla* | 2.0-4.0 |
| Oleander | *Nerium oleander* | 2.0-4.0 |
| Chinese hibiscus | *Hibiscus rosa-senensis* | 2.0-4.0 |
| Sweet pea | *Lathyrus odoratus* | 2.0-4.0 |
| Carnation | *Dianthus caryophyllus* | 2.0-4.0 |
| **Tolerant** | | |
| Indian hawthorn | *Raphiolephis indica* | 6.0-8.0 |
| Natal palm | *Carissa grandiflora* | 6.0-8.0 |
| Oxalis | *Oxalis bowiei* | 6.0-8.0 |

1 Species listed in order of increasing tolerance based on appearance as well as growth reduction.
2 Boron concentrations exceeding the threshold may cause leaf burn and loss of leaves.

TABLE 19
**Citrus and stone fruit rootstocks ranked in order of increasing boron accumulation and transport to scions** (after Maas 1990)

| Common name | Botanical name |
|---|---|
| **Citrus** | |
| Alemow | *Citrus macrophylla* |
| Gajanimma | *C. pennivesiculata or C. moi* |
| Chinese box orange | *Severina buxifolia* |
| Sour orange | *C. aurantium* |
| Calamondin | *x. Citrofortunella mitis* |
| Sweet orange | *C. sinensis* |
| Yuzu | *C. junos* |
| Rough lemon | *C. limon* |
| Grapefruit | *C. x paradisi* |
| Rangpur lime | *C. x limonia* |
| Troyer citrange | *x Citroncirus webberi* |
| Savage citrange | *x Citroncirus webberi* |
| Cleopatra mandarin | *C. areticulata* |
| Rusk citrange | *x Citroncirus webberi* |
| Sunki mandarin | *C. reticulata* |
| Sweet lemon | *C. limon* |
| Trifoliate orange | *Poncirus trifoliata* |
| Citrumelo 4475 | *Poncirus trifoliata x C. paradisi* |
| Ponkan mandarin | *C. reticulata* |
| Sampson tangelo | *C. x tangelo* |
| Cuban shaddock | *C. maxima* |
| Sweet lime | *C. aurantiifolia* |
| **Stone fruit** | |
| Almond | *Prunus dulcis* |
| Myrobalan plum | *P. cerasifera* |
| Apricot | *P. armeniaca* |
| Marianna plum | *P. domestica* |
| Shalil peach | *P. persica* |

TABLE 20
**Chloride tolerance of agricultural crops. Listed in order of increasing tolerance** (after Maas 1990)

| Crop | Maximum $Cl^-$ concentration[1] without loss in yield (threshold) $mol/m^3$ | Percent decrease in yield at $Cl^-$ concentrations[1] above the threshold; (slope) % per $mol/m^3$ |
|---|---|---|
| Strawberry | 10 | 3.3 |
| Bean | 10 | 1.9 |
| Onion | 10 | 1.6 |
| Carrot | 10 | 1.4 |
| Radish | 10 | 1.3 |
| Lettuce | 10 | 1.3 |
| Turnip | 10 | 0.9 |
| Rice, paddy[2] | 30[3] | 1.2[3] |
| Pepper | 15 | 1.4 |
| Clover, strawberry | 15 | 1.2 |
| Clover, red | 15 | 1.2 |

TABLE 20 Cont'd

| Crop | Maximum $Cl^-$ concentration[1] without loss in yield (threshold) $mol/m^3$ | Percent decrease in yield at $Cl^-$ concentrations[1] above the threshold; (slope) % per $mol/m^3$ |
|---|---|---|
| Clover, alsike | 15 | 1.2 |
| Clover, ladino | 15 | 1.2 |
| Maize | 15 | 1.2 |
| Flax | 15 | 1.2 |
| Potato | 15 | 1.2 |
| Sweet potato | 15 | 1.1 |
| Broad bean | 15 | 1.0 |
| Cabbage | 15 | 1.0 |
| Foxtail, meadow | 15 | 1.0 |
| Celery | 15 | 0.6 |
| Clover, Berseem | 15 | 0.6 |
| Orchardgrass | 15 | 0.6 |
| Sugarcane | 15 | 0.6 |
| Trefoil, big | 20 | 1.9 |
| Lovegrass | 20 | 0.8 |
| Spinach | 20 | 0.8 |
| Alfalfa | 20 | 0.7 |
| Sesbania[2] | 20 | 0.7 |
| Cucumber | 25 | 1.3 |
| Tomato | 25 | 1.0 |
| Broccoli | 25 | 0.9 |
| Squash, scallop | 30 | 1.6 |
| Vetch, common | 30 | 1.1 |
| Wildrye, beardless | 30 | 0.6 |
| Sudangrass | 30 | 0.4 |
| Wheatgrass, standard crested | 35 | 0.4 |
| Beet, red[2] | 40 | 0.9 |
| Fescue, tall | 40 | 0.5 |
| Squash, zucchini | 45 | 0.9 |
| Hardinggrass | 45 | 0.8 |
| Cowpea | 50 | 1.2 |
| Trefoil, narrow-leaf birdsfoot | 50 | 1.0 |
| Ryegrass, perennial | 55 | 0.8 |
| Wheat, Durum | 55 | 0.5 |
| Barley (forage)[2] | 60 | 0.7 |
| Wheat[2] | 60 | 0.7 |
| Sorghum | 70 | 1.6 |
| Bermudagrass | 70 | 0.6 |
| Sugarbeet[2] | 70 | 0.6 |
| Wheatgrass, fairway crested | 75 | 0.7 |
| Cotton | 75 | 0.5 |
| Wheatgrass, tall | 75 | 0.4 |
| Barley[2] | 80 | 0.5 |

NB: These data serve only as a guideline to relative tolerances among crops. Absolute tolerances vary depending upon climate, soil conditions and cultural practices.

1 $Cl^-$ concentrations in saturated soil extracts samples in the rootzone. To convert $Cl^-$ concentrations to ppm, multiply threshold values by 35. To convert % yield decreases to % per ppm, divide slope values by 35.

2 Less tolerant during emergence and seedling stage.

3 Values for paddy rice refer to the $Cl^-$ concentration in the soil water during the flooded growing conditions.

TABLE 21
**Chloride tolerance limits of some fruit crop cultivars and rootstocks** (after Maas 1990)

| Crop | Rootstock or cultivar | Maximum permissible $Cl^-$ in soil water without leaf injury[1] ($mol/m^3$) |
|---|---|---|
| **Rootstocks** | | |
| Avocado | West Indian | 15 |
| (*Persea americana*) | Guatemalan | 12 |
| | Mexican | 10 |
| **Citrus** | Sunki mandarin, grapefruit | 50 |
| (*Citrus* sp.) | Cleopatra mandarin, Rangpur lime | 50 |
| | Sampson tangelo, rough lemon[2] | 30 |
| | Sour orange, Ponkan mandarin | 30 |
| | Citrumelo 4475, trifoliate orange | 20 |
| | Cuban shaddock, Calamondin | 20 |
| | Sweet orange, Savage citrange | 20 |
| | Rusk citrange, Troyer citrange | 20 |
| **Grape** | Salt Creek, 1613-3 | 80 |
| (*Vitis* sp.) | Dog ridge | 60 |
| **Stone fruit** | Marianna | 50 |
| (*Prunus* sp.) | Lovell, Shalil | 20 |
| | Yunnan | 15 |
| **Cultivars** | Boysenberry | 20 |
| Berries[3] | Olallie blackberry | 20 |
| (*Rubus* sp.) | Indian Summer raspberry | 10 |
| **Grape** | Thompson seedless, Perlette | 40 |
| (*Vitis* sp.) | Cardinal, black rose | 20 |
| **Strawberry** | Lassen | 15 |
| (*Fragaria* sp.) | Shasta | 10 |

1 For some crops, these concentrations may exceed the osmotic threshold and cause some yield reduction.
2 Data from Australia indicate that rough lemon is more sensitive to $Cl^-$ than sweet orange.
3 Data available for one variety of each species only.

## Effects of Salts on Crop Quality

Information on the effects of water salinity and/or soil salinity on crop quality is very scant although such effects are apparent and have been noticed under field conditions. In general, soil salinity, either caused by saline irrigation water or by a combination of water, soil and crop management factors, may result in: reduction in size of the produce; change in colour and appearance; and change in the composition of the produce.

Shalhevet *et al.* (1969) reported a reduction of seed size in groundnuts beginning at soil salinity levels ($EC_e$) of 3 dS/m. However, there is an increase in seed oil content with increasing salinity up to a point. Table 22 illustrates these effects.

In the case of tomatoes, it was reported (Shalhevet and Yaron 1973) that for every increase in 1.5 dS/m in mean $EC_e$ beyond 2 dS/m, there was a 10 percent reduction in yield. The yield reduction was due only to reduction in fruit size and weight and not to reduction in fruit number. However, there was a marked increase in soluble solids in the extract, which may be an important criterion for tomato juice production. If ever tomato juice processors purchase tomatoes on the basis of total solids content, there would be no economic penalty for salinity in the range up to 6.0 dS/m in $EC_e$. Table 23 presents the results of this investigation.

TABLE 22
**Effect of soil salinity on seed weight and oil content in groundnuts** (Shalhevet *et al.* 1969)

| $EC_e$ dS/m | Weight of 1000 seeds, g | Oil content % dry weight |
|---|---|---|
| 1.74 | 774 | 48.9 |
| 2.92 | 690 | 49.0 |
| 3.16 | 676 | 50.2 |
| 4.41 | 656 | 47.6 |
| 5.61 | 470 | 46.2 |

The mean pH of the juice was 4.3 with no meaningful differences among treatments. Fruits from higher salinity treatments were less liable to damage and the number of spoiled fruits was less.

Table 23
**Effect of soil salinity on fruit weight and soluble solid content of tomatoes**

| $EC_e$ dS/m | Weight per fruit g | % soluble solids | % spoiled fruits |
|---|---|---|---|
| 1.6 | 68.5 | 4.5 | 15.5 |
| 3.8 | 59.5 | 4.5 | 17.7 |
| 6.0 | 55.8 | 4.8 | 12.3 |
| 10.2 | 51.9 | 5.9 | 11.1 |

Meiri *et al.* (1981) reported that increased salinity reduced fruit size in muskmelons (*Cucumis melo*). However, ripening was accelerated by salinity. Bielorai *et al.* (1978) reported that grapefruit yield decreased with increase in chloride ion concentration; the yield reduction was caused more by reduction in fruit size and weight. Salinity effects on fruit quality were similar to those caused by water stress. Comparing the low and high salinity levels, there is an increase in soluble solids and tritratable acidity in the juice. There were no differences in juice content. Rhoades *et al.* (1989) obtained increases in the quality of wheat, melons and alfalfa from use of saline drainage water for irrigation.

## CRITERIA, STANDARDS AND CONSIDERATIONS IN THE ASSESSMENT OF THE SUITABILITY OF SALINE WATER FOR IRRIGATION AND CROP PRODUCTION

According to Ayers and Westcot (FAO 1985), waters of greater than 3 dS/m in EC are severely restricted in their use for irrigation. However, as reviewed in Chapter 3, waters of many different compositions ranging in salinity up to at least 8 dS/m ($\approx$ 6000 mg/l TDS) are being used productively for irrigation in numerous places throughout the world under widely varying conditions of soil, climate, irrigation and cropping. This is evidence of the fact that the actual suitability of a given water for irrigation greatly depends on the relative need and economic benefit that can be derived from irrigation with the saline water compared to other alternatives and on the specific conditions of use. Important conditions of use include the crop being grown, various soil properties, irrigation management practices, climatic conditions, and certain cropping and soil management practices. This is also evidence of the limited usefulness of generalized water classification schemes and it illustrates the need for a more quantitative means of assessing water suitability for irrigation; one that takes into better account some of these specific conditions of use.

The ultimate method of assessing the suitability of saline water for irrigation requires:

- prediction of the composition, osmotic and matric potential of the soil water (both in time and space) within the rootzone and the physical condition (permeability, crusting, tilth, etc.) of the soil that results from the interplay of irrigation, rainfall, leaching, drainage, water table lowering, evapotranspiration, soil physical and mineralogical properties and plant growth;

- knowledge of how resulting soil conditions affect the suitability for irrigation and crop production and of how any crop would grow and yield under such soil and climatic conditions (Rhoades 1972). It is the lack of quantitative capabilities in this regard that has resulted in the more general use made of empirical approaches to evaluate irrigation water quality.

## Criteria and Standards for Assessing Suitability of Saline Water for Irrigation

The suitability of a water for irrigation should be evaluated on the basis of criteria indicative of its potential to create soil conditions hazardous to crop growth (or to animals or humans consuming those crops). Relevant criteria for judging irrigation water quality in terms of potential hazards to crop growth are primarily:

- **Permeability and tilth** The interactive, harmful effects of excessive exchangeable sodium and high pH in the soil and low electrolyte concentration in the infiltrating water on soil structure, permeability and tilth. These effects are evidenced by disaggregation, crusting, poor tilth (coarse, cloddy and compacted topsoil aggregates) and by a reduced rate of water infiltration.

- **Salinity** The general effect of salts on crop transpiration and growth which are thought to be largely osmotic in nature and, hence, related to total salt concentration rather than to the individual concentrations of specific salt constituents. These effects are generally evidenced by reduced transpiration and proportionally retarded growth, producing smaller plants with fewer and smaller leaves.

- **Toxicity and nutritional imbalance** The effects of specific solutes, or their proportions, on plant growth, especially those of chloride, sodium and boron. These effects are generally evidenced by leaf burn and defoliation.

The suitability of the water for irrigation is evaluated in terms of the permeability and crusting hazards using $EC_{iw}$ and estimates of the ESP (or SAR) that will result in the topsoil and permissible limits of ESP ($SAR_{sw}$, $SAR_{iw}$ or adjusted $SAR_{iw}$), $EC_{iw}$ and pH for the conditions of use. Soil permeability problems are deemed likely if the ESP - $EC_{iw}$ combination lies to the left of a threshold relation between $SAR_{sw}$ (ordinate) and $EC_{iw}$ (abscissa) of the type shown in Figure 2. Since the $SAR_{sw}$ - $EC_{iw}$ threshold relations of many soils may differ from that given in Figure 2 (Suarez 1990), specific relations should be used for the specific soils of interest; Figure 2 should only be used if specific relations are not available. Note that the permeability hazard threshold relation curves downward at low $SAR_{sw}$ values (about 10) and intersects the $EC_{iw}$ axis at some positive value (about 0.3) because of the dominating effect of electrolyte concentration on soil aggregate stability, dispersion and crusting at low salinities.

Until more information is available on how crops respond to time and space varying osmotic and matric stresses as a function of irrigation management, soil water retentivity characteristics and atmospheric stresses, and practical dynamic models are developed to predict these stresses, the following parameters are recommended for evaluating the salinity and toxicity hazards of irrigation waters. For near steady-state, flood irrigation regimes in which significant matric stresses are achieved during the irrigation cycle, average rootzone $EC_e$ (or average solute concentration in the case of $Cl^-$ and B toxicities) should be estimated for any given water and irrigation management practice and used to assess the likelihood of yield reduction of any given crop by comparison with threshold values of $EC_e$ (or $Cl^-$ and B) given in Tables 10 to 17. For near steady-state, flood irrigation regimes where significant matric stresses are avoided, as results with high-frequency drip irrigation, either water-uptake-weighted electrical conductivity, $EC^*_e$, or osmotic potential, $\pi^*$, are appropriate indices of salinity (as are Cl* and B* for toxicity considerations) that should be calculated and used to assess the likelihood of yield reduction. For dynamic, non-steady-state flood irrigation regimes, though total soil water potential is more appropriate as an index to judge crop response, average rootzone levels of salinity, or osmotic potential, (or $Cl^-$ and B) are also reasonable indices to calculate and use to assess the likelihood of salinity (or toxicity) problems resulting from irrigating with saline waters. Because of the demonstrated ability of the chemistry model "Watsuit" to predict either $EC^*_e$ or $\pi^*$, and average rootzone salinity (and $Cl^-$ and B concentrations), it is used herein for assessing the suitabilities of waters for irrigation. Use of this model is described later, as is a non-computer version for more approximative needs. For sprinkler or spray irrigation systems, the foliar burn hazards should be considered using the data given in Table 16.

## Considerations in Assessing Permeability and Tilth Hazards

ESP and pH are important properties of soils which influence soil permeability and tilth. Therefore, any suitable evaluation of the potential permeability hazard of a sodic, saline irrigation water must relate some property of the irrigation water to the ESP (ideally, also pH) that will result in the soil from use of that water. Surface soil ESP values are of most concern for assessing soil permeability problems, because water intake and transmissibility are most generally limited by surface soil properties. The surface soil ESP level resulting from irrigation is more easily predicted than at deeper rootzone levels because it is essentially independent of leaching fraction. Since the sodium adsorption ratio of the soil water ($SAR_{sw}$) is related to the ESP of soils (the two are nearly equivalent over the relevant range of 0 - 30), $SAR_{sw}$ has been used advantageously in place of ESP for predicting sodicity-related problems (US Salinity Laboratory Staff 1954). The residual sodium carbonate, RSC, index is not generally suitable for this purpose for the reasons given elsewhere (Oster and Rhoades 1977).

For approximative purposes, the SAR of the saline irrigation water ($SAR_{iw}$) itself may be substituted in this regard, since it is relatable to the resultant $SAR_{sw}$ in the soil. $SAR_{sw}$ is typically higher than $SAR_{iw}$ in the deeper soil depths, due to the concentrating effects of evaporation and transpiration, the incorporation and decomposition of plant residues in the topsoil, and the loss of Ca and Mg salts from the irrigation water due to precipitation of alkaline earth carbonates and gypsum upon concentration. It may sometimes be lower than expected (but more rarely so for saline waters) due to the introduction of Ca, Mg, $SO_4$ and $HCO_3$ into the soil water from the dissolution and weathering of soil minerals. These effects limit the applicability of $SAR_{iw}$ as a generally-suitable index of $SAR_{sw}$ to the topsoil and to saline, low carbonate waters.

For more quantitative purposes, $SAR_{sw}$ (essentially ESP) should be calculated from irrigation water composition and leaching fraction using the model (Watsuit) provided herein. Alternatively, the adjusted sodium adsorption ratio (adj. $SAR_{iw}$) can be used to estimate $SAR_{sw}$ without the aid of a computer. Both give essentially equivalent results.

It is not now possible to provide more exact quantitative standards for assessing the permeability hazard than those given in Figure 2 because of the lack of quantitative information on the interplay of exchangeable sodium, electrolyte concentration, pH and various other soil properties on soil permeability, aggregation and tilth. Most of the available information on this subject is based on saturated hydraulic conductivity and aggregate stability data determined on sieved soil samples in laboratory studies. Such data do not necessarily represent field conditions. Less is known about the effects of exchangeable sodium, electrolyte concentration, pH, etc. on unsaturated soil hydraulic conductivity. Additionally, little is known about how the distribution of exchangeable sodium, electrolyte concentration, pH, etc. within the profile affects soil permeability. While it is generally assumed that the surface horizon limits infiltration, it is possible that excessive levels of exchangeable sodium in the deeper strata, especially in clay pans, may be restrictive in some soils, especially those with non-uniform texture and structure. It is known that even soils having similar textures and cation exchange capacities may vary considerably in their vulnerabilities to permeability losses and aggregate degradation due to sodicity. Differences in clay mineralogy is one cause of such variation. Additional causes are the effects of various cementing materials (such as organic matter and calcareous-, siliceous-, and oxide-compounds) on soil aggregate stability and clay dispersion (Goldberg *et al.* 1990). Such materials tend to stabilize soil structure, but adequate quantification of their effects on structural and permeability properties of soils is lacking. Some of the variations are caused by the mechanical effects of tillage and other cultural practices, such as sprinkler water impact, on surface sealing, as influenced by exchangeable sodium, electrolyte concentration, etc. In many semi-arid regions the irrigation season is followed by a rainy season. During the irrigation season the high electrolyte concentration of the saline irrigation waters usually prevents excessive aggregate slaking, soil swelling and clay dispersion. However, when the saline water is replaced by rain or a non-saline irrigation water, a $SAR_{sw}$ - $EC_{iw}$ situation conducive to disaggregation, dispersion and crusting can result, especially in the topsoil. Insufficient research has been directed toward prediction of this type of response (periodic infiltrations of non-saline water in sodic, saline soils), with resulting limitations in the ability to predict permeability and crusting problems for such conditions. The various factors influencing the permeability hazard are reviewed in more detail by Shainberg (1984), Suarez (1990) and Pratt and Suarez (1990).

## Considerations in Assessing Salinity and Toxicity Hazards

Saline water rarely contains enough salts to cause immediate injury to crops, unless foliar contact occurs. Such water may contain 4 metric tons of salts per thousand $m^3$ or more, and is generally applied to soils at annual application rates of 10 to 15 thousand $m^3$/ha. Thus, 60 metric tons or more of salt per hectare may be added to soils annually from irrigation with such saline waters. The concentration of soluble salts in such irrigated soils increases with water application and evapotranspiration rates, because the salt is left behind as most of the applied water is removed by evaporation and transpiration. Thus salinity problems can develop over time from use of saline water for irrigation without proper management.

Indeed, without provision for leaching, salts will increase in the soil water with successive irrigations until the solubility limit of each salt-mineral is reached. The solubilities of many salts, such as the chlorides and sulphates of sodium, magnesium and potassium, are above the salinity tolerance limits of most plants. However, the relatively low solubilities of calcium carbonate and calcium sulphate limit the concentrations of Ca, $HCO_3$ and $SO_4$ in soil waters (Oster and Rhoades 1975; 1977). The effects of salt precipitation may be significant at leaching fractions of 0.2 and less with irrigation waters of more than about 2 dS/m electrical conductivity ($EC_{iw}$), if the waters contain substantial amounts and proportions of Ca, $HCO_3$ and $SO_4$ solutes. Knowing how much of the salt added in the irrigation water precipitates in the soil, or is removed by leaching, can be an important consideration. Losses by precipitation can be substantial, especially when saline, gypsiferous waters are used for irrigation and where the leaching is less than about 20 percent. With leaching (which may be achieved with over-irrigation or rainfall), the degree of accumulation of salts in soil water can be lessened and controlled within limits. Hence, the amount of soil water salinity resulting from the use of a saline irrigation water is related primarily to its salt content and composition, the amounts of water applied and the extent of leaching achieved (Rhoades *et al.* 1973; 1974). For the above reasons, the assessment of the suitability of a saline water for irrigation should be made in view of:

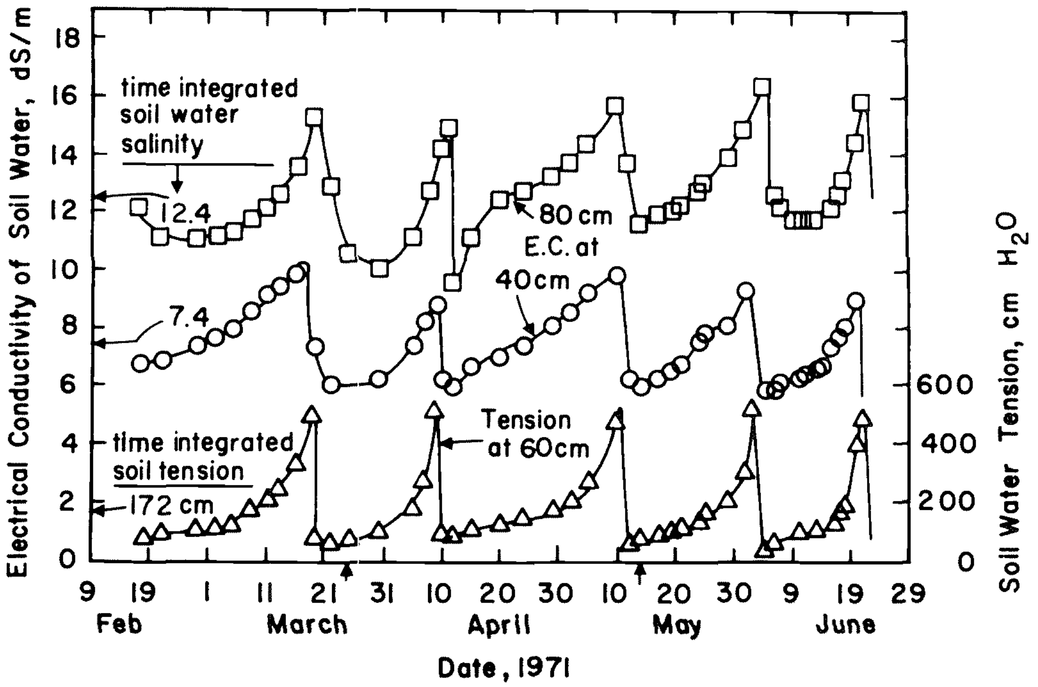
- what level of salinity will result in the soil water considering the initial levels, the amount and salinity of the applied water, resultant chemical reactions and leaching; and
- how much salinity (and potentially toxic solute concentrations) the crop can tolerate in the soil water.

As explained earlier, crops vary in their salt tolerance. Since there is approximately a ten-fold range in salt tolerance of crops (see Tables 10 to 17), a comparable range in the permissible salinities of irrigation waters might be expected, depending on the crop being grown and other factors being equal. An important consideration in evaluating the salinity and toxicity hazards of an irrigation water is the appropriateness of the method used to bring the salt and toxicity tolerances of the crop being grown into account in the assessment. Most of the data on salt tolerances of crops given in this publication were determined for growth following seedling establishment and under relatively favourable reference conditions. The following are typical conditions:

- □ Crops were grown in a climate characterized by little rainfall (and that falling primarily in the non-growing season), relatively high temperatures and low relative humidities.
- □ High leaching fractions (LF, the fraction of applied and infiltrated water that passes through the rootzone) were achieved (approximately 50 percent) using high pre-plant and in-season irrigations and a soil with good infiltration, permeability, and drainage properties; thus relatively uniform soil salinity levels were established following seedling establishment (the range of salinity within the rootzone was typically about ± 10 percent of the mean).
- □ Seedlings were established under low salinity conditions by appropriate cultural techniques and usually with pre-plant and frequent early-season irrigations made using low-salinity waters.
- □ Recommended optimum cultural practices for non-saline conditions were used with respect to fertilization, irrigation frequency, growing season, plant density, etc.
- □ Crop yields were related to average rootzone salinities as measured by electrical conductivity of soil saturation paste extracts. Matric stress is incorporated in the reference conditions in an unspecified way, though it was usually relatively low compared to the osmotic stress.

Under steady-state and ideal field conditions, soil water salinity (or toxic ion concentration) generally ranges from a low level not greatly exceeding that of the irrigation water near the soil surface to levels many times the irrigation water level at the bottom of the

FIGURE 4
Variations in *in situ* soil water EC and tension (cm $H_2O$) in rootzone of alfalfa crop during spring and respective integrated values




rootzone. It also varies with time as the water is consumed by the plant and then replenished by irrigation (see Figure 4, after Rhoades 1972). Matric stresses may also occur concomitantly. To assess how a plant will respond to salinity (that of the irrigation water or that in the soil water) under non-steady-state conditions, some hypothesis of how crops respond to non-uniform salinity stresses separately and in combination with matric stresses, both in time and space, must be used. The following information and concepts are relevant for this purpose.

As water is removed from a soil of non-uniform salinity, the total potential of the water being absorbed by the plant tends towards a uniform value in all depths of the rootzone, even though the components of the total potential (osmotic and matric) may vary inversely among the depths (Wadleigh and Ayers 1945; Richards and Wadleigh 1952). In irrigated soils where salinity increases with depth, most of the water uptake is from the upper, less saline soil depths until sufficient water is removed to lower the matric water potential to a point where, when combined with the also decreasing osmotic potential, the total water potential at some lower depth (although having a lower osmotic potential) becomes less inhibitive. At this latter time, salinity effects *per se* on plant-water availability and, hence, on crop growth become greater. With this in mind it could be surmised that:

- plants should tolerate higher levels of salinity under conditions of high matric potential (low matric stress);
- high soil water salinities occurring in deeper regions of the rootzone should be substantially offset if sufficient, low-salinity water is available in, or added fast enough to, the upper profile depths to meet the crop's evapotranspiration requirement;

- the level of salinity that can be tolerated in the soil water (hence in the irrigation water) will depend not only on the salt tolerance of the crop to be grown, but also on the initial content and distribution of salinity in the soil profile, on the amount and frequency of irrigation, on the extent to which the soil water is depleted between irrigations, and on the water content and matric properties of the soil.

The last two factors are important because both the matric and osmotic potentials of soil water decrease (stresses increase) as the water content decreases with plant extraction and because these two potentials are approximately additive in their effects on plant growth inhibition (Shalhevet 1984). Thus, we can see why irrigation management should affect permissible levels of salinity in irrigation waters.

While frequency of irrigation is one facet of management that one would expect (based on the preceding reasoning) to markedly affect crop response to saline water, the evidence is contradictory. Several studies have shown no better yield with high irrigation frequency compared to normal frequency (Shalhevet 1984). Yaron *et al.* (1972), Bresler and Yaron (1972) and Zur and Bresler (1973) evaluated the interactions of irrigation frequency, level of initial soil salinity, water and climatic conditions, and the short-term use of variably salinized irrigation waters without leaching on grapefruit and groundnut yields by both statistical and computer simulation techniques. They concluded that osmotic potential, $\pi$, was overwhelmingly dominant on the fruit yield of these crops under conditions of short irrigation intervals (3 days) in the absence of leaching. For such short irrigation intervals, the integrated matric potential, $\tau$, was only 10 to 15 percent of the integrated total water potential, $\phi$. However, $\tau$ increased to about 80 percent of the integrated $\phi$ at longer irrigation intervals (about 20 to 30 days). They found that irrigation water quality and initial level of soil salinity became less important (as compared with $\tau$) on $\phi$, as the irrigation interval increased - becoming nearly negligible at the longest irrigation interval. From these observations they concluded that the salt concentration of the soil water existing before irrigation was initiated primarily determines the value of the time-integrated $\pi$ under conditions of short-term irrigation with saline water and absence of leaching. For this reason, they advocated using an extra allotment of water to preleach the soil, so as to reduce the level of soil salinity existing at the beginning of the crop season, rather than using this same amount of water for leaching during the irrigation season. As will be discussed later, the cyclic use of non-saline water for pre- and early-season irrigation with leaching followed by the use of saline water with minimal leaching is advocated as an effective strategy for maximizing the use of multiple water supplies for irrigation. The above findings help explain how this strategy minimizes salinity stress resulting from irrigating with saline waters.

Use of drip irrigation, in which water is applied at a high frequency and sufficient rate to keep $\tau$ high while meeting evapotranspiration requirements, appears to permit crops to be grown more successfully with saline waters than otherwise possible (Goldberg and Gornet 1971; Gornet *et al.* 1971 and Bernstein and Francois 1973a; Shalhevet 1984). The success of this method is believed to stem from the fact that it keeps both the matric- and the osmotic-potentials relatively higher over time by avoiding substantial drying cycles between irrigations.

On the other hand, increased irrigation frequency typically results in a decreased depth of rooting, an upward shift of the peak of the salt distribution profile and an increase in the mean salt concentration in the upper, main part of the rootzone. It increases the load of salt in the more limited soil volume, hence it increases soil salinity in the effective rootzone. Thus, in some cases, the net result of increasing irrigation frequency may be to increase soil salinity and its deleterious effects upon crop growth. The net overall effect on time- and depth-weighted, osmotic- and matric-potentials is not easy to predict. This is an area of understanding that needs improvement. Additional research should be carried out to predict better if, when and by how much irrigation frequency can be increased to reduce salinity and matric stresses on crop production.

Leaching requirement is another facet of irrigation management, besides irrigation frequency, that influences crop response to irrigation water salinity which is also not sufficiently understood, especially when its interactions with irrigation frequency are jointly considered. Under conditions of long-term use of saline waters for irrigation (steady-state conditions), it is primarily the interaction between salt concentration of the irrigation water and the leaching fraction that determines the concentration and distribution of soil salinity within the rootzone, as well as the "depth-averaged" value of osmotic water potential. This conclusion is supported by much experimental evidence (see Figures 5 and 6, after Bower *et al.* 1969). Leaching fraction is also the major management factor affecting the "water-uptake-weighted" salinity. This can be deduced from the equation developed by Bernstein and Francois (1973b) to describe the mean salt concentration against which water is absorbed by a plant, $\overline{C}$:

$$\bar{C} = \frac{-1}{V_{iw} - V_{dw}} \int_{V_{iw}}^{V_{dw}} C_{dv} = \frac{C_{iw}}{1 - LF} \ln\left(\frac{1}{LF}\right) \qquad (2)$$

where $V_{iw}$ and $V_{dw}$ are volume of infiltrated and drainage water, respectively, and $C_{iw}$ and Cdw are the concentrations of the irrigation and drainage waters, respectively. Since concentration, EC and osmotic potential are closely related, equation [2] can also be used to calculate $\pi$ weighted in proportion to water uptake.

Equation [2] applies only to the condition of conservation of mass, i.e. $C_{iw} V_{iw} = C_{dw} V_{dw}$. It can be modified to account for the effects of salt precipitation and dissolution as follows (after Ingvalson *et al.* 1976):

$$\bar{C} = a - \frac{b}{(1 - LF)} \ln(LF) + \frac{c}{(LF)} \qquad (3)$$

where a, b, and c are empirical constants of the second-order polynomial equation describing the concentration of a particular irrigation water as a function of (1/LF) derived from the Watsuit model described in the following section.

Under the assumption of piston flow, $\overline{C}$ is independent of the water uptake distribution, frequency of irrigation and time, because it is only the relation between concentration and volume during transpiration that affects $\overline{C}$ as the unit volume of applied water is consumed during passage through the rootzone (Rhoades and Merrill 1976). The degree to which volume is reduced and concentration is increased during this passage is determined solely by the leaching fraction and is independent of time or the extent to which the soil is dried between irrigations. This conclusion agrees with the observational and model findings of Zur and Bresler (1973). However, $\overline{C}$ is not correctly described by Equations [2] and [3] where dispersion and diffusion appreciably affect the distribution of salinity in the rootzone (Raats 1974).

**FIGURE 5**
**Steady-state soil profile expressed as EC of the soil saturation extract, as influenced by EC of irrigation water and leaching fraction**

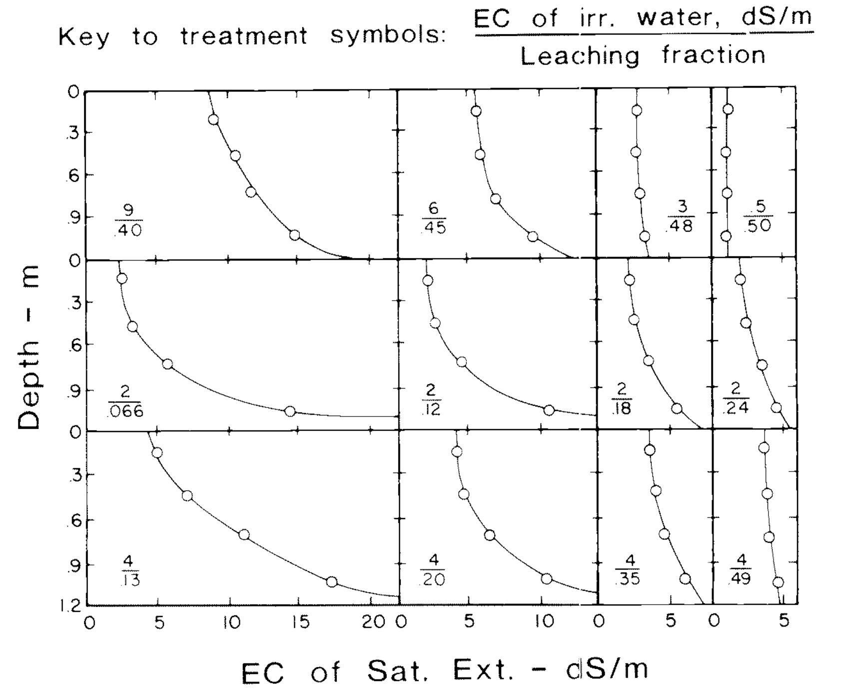
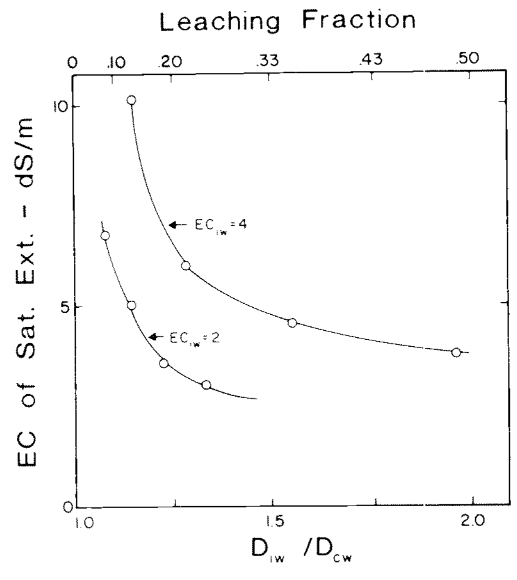



**FIGURE 6**
**Relationship between average rootzone salinity expressed as EC of soil saturation extract and leaching fraction for two irrigation water concentrations**



Because $\overline{C}$ is more strongly a function of $C_{iw}$ than of LF, (see Equations 2 and 3), Bernstein and Francois (1973b) concluded that crop growth is more sensitive to $EC_{iw}$ than average rootzone salinity and that high salinity levels in the lower depths of the rootzone have little effect on yield. This conclusion overlooks the effects that LF and irrigation frequency may have on $\tau$ and $\pi$ distributions within the rootzone and, hence, on crop response to salinity, when significant soil drying occurs between irrigations. In the case of negligible $\tau$, such as under conditions of high frequency trickle irrigation regimes, $\overline{C}$ is probably a better index of salinity than the average rootzone value for evaluating expected crop response. However under conditions of infrequent irrigation, the opposite is more likely true, as discussed below. Time of exposure to salinity stress is also ignored in Equations [2] and [3]. This factor is also discussed below.

The appropriateness of various indices of salinity for assessing water-suitability for irrigation is affected by soil water retentivity characteristics, irrigation frequency, leaching fraction and irrigation water salinity, as shown by the conceptual modelling study of Rhoades and Merrill (1976). Details of the assumptions and methods used in this study are described in FAO (1976). Results of the steady-state model predictions for representative types of soils, irrigation waters and irrigation frequencies showed the following:

- The lower the EC of the irrigation water and the higher the LF used with the water, the higher is the resultant water-uptake-weighted osmotic potential and the lower is the total water stress to which a plant is exposed at steady-state. The resulting increase in $\bar{\pi}$ that occurs as LF is increased would be expected, in many cases, to increase crop yield.

- For any given $EC_{iw}$, leaching fraction affects the need for increased frequency of irrigation because it affects the availability of water primarily in the lower rootzone depths where $\pi$ is low, while having little effect in the upper rootzone where most of the water uptake occurs; hence, $\bar{\tau}$ is not greatly affected by LF, except under conditions of marked water depletion between irrigations, i.e. with very low frequency irrigation.

- While $\bar{\tau}$ is not appreciably affected by LF, it is significantly influenced by $EC_{iw}$ and the total water potential used as a set point for scheduling an irrigation, $\phi_f$. $\bar{\tau}$ decreases with $\phi_f$ and, at any given level of $\phi_f$, increases with increasing $EC_{iw}$. The drier the soil becomes between irrigations (i.e. the longer the irrigation interval and the lower $\phi_f$ is), the greater will be the degree of water depletion and hence the lower $\bar{\tau}$ will be. Furthermore, the lower $EC_{iw}$ is, the higher is the osmotic potential in the upper part of the rootzone where most of the water is absorbed and hence the greater is the extent of water depletion there for any fixed level of $\phi_f$ (frequency of irrigation).

- Retentivity characteristics of different soil types may have important effects on $\overline{\phi}$ because of their effect on $\bar{\tau}$. Retentivity characteristics have less effect, however, on the extent of water depletion, especially under conditions of high $\phi_f$ (i.e. for high frequency irrigation). This is so because with water uptake by the crop shortly after irrigation, a considerable decrease in water content causes only a minor increase in total water stress; however, later on when a substantial fraction of the available moisture has been used, any further additional loss of moisture from the soil causes a relatively large increase in total water stress.

- For cases of infrequent irrigation, the greater the salinity of the irrigation water, the longer the period the crop is exposed to total soil water potentials less than some arbitrary critical value. As reviewed by Slayter (1969) and Rawlins and Raats (1975), time of exposure to salinity or salinity exceeding some "critical" value affects crop response. Correlations have been observed between "stress days", expressed in terms of total water potential, and crop yields. The duration of such exposure to excessive stress can be appreciably reduced by increasing the leaching fraction with which a saline irrigation water is used. The benefit of LF is clearly apparent in this regard. These results support the value of increasing LF to minimize some of the deleterious consequences of irrigating with saline waters, at least for steady-state conditions.

Based on the above, the following conclusions emerge for steady-state conditions:

- $EC_{iw}$ and LF combine to establish the level and distribution of osmotic stress in the rootzone and the value of $\bar{\pi}$; they also affect $\bar{\phi}$;

- leaching fraction has little effect on $\bar{\tau}$, but irrigation frequency, extent of water depletion between irrigations, and soil water retentivity characteristics do;

- duration of stress, such as "stress days", is affected by irrigation water salinity, leaching fraction, frequency of irrigation, and soil water retentivity characteristics;

- while the importance of these indices of water status on crop response may vary with crop tolerance, water composition, soil properties and climatic stress conditions, it seems justified to conclude that, where saline waters are used for irrigation, LF should be increased to increase $\pi$ (and $\bar{\pi}$) and (all else being equal) frequency of irrigation should be increased to increase $\tau$ (and $\bar{\tau}$), the two combining to maximize $\phi$ (and $\bar{\phi}$) and minimize duration of "stress days";

- space-averaged salinity should be a reasonably good index of crop response to soil water salinity in cases where matric stress is significant, such as with infrequent irrigation, because of the marked dependence of duration of "stress days" on LF. This is so because LF primarily affects the level of salinity in the lower depths of the rootzone; therefore, a parameter of salinity that is related to the space distribution of salinity, especially lower rootzone salinity, should be used as an appropriate index to estimate crop response for the case of infrequent irrigation;

- duration of stress increases and less opportunity is allowed for growth "catch-up" as the irrigation interval is extended. The increased osmotic pressure associated with lower LFs and the use of more saline irrigation waters becomes especially disadvantageous then, because the "critical stress" level of $\phi$ will be reached quicker (for a given amount of water use) when the initial level of $\pi$ present at the start of water depletion is high compared to when it is low;

- under conditions of more frequent irrigation, crop response should become relatively more responsive to $EC_{iw}$ and $\bar{\pi}$ than to LF and depth averaged salinity. Some experimental results appear to substantiate this (Meiri 1984; Bresler and Hoffman 1986; Bresler 1987).

Bower *et al.* (1969; 1970) concluded from their studies that crop response to salinity can be related to average rootzone salinity. Ingvalson *et al.* (1976) correlated alfalfa yield obtained under conditions of non-uniform rootzone salinity to various indices of salinity including: (i) irrigation water salinities, (ii) depth averaged, soil profile salinities, (iii) soil water salinities weighted in accordance with the water uptake pattern of the crop, and (iv) time and space integrated soil water salinities. Alfalfa yield actually correlated better with

TABLE 24

**Correlation of crop response with various indices of salinity under conditions of non-uniform rootzone salinity and conventional irrigation frequencies** (after Rhoades and Merrill 1976)

| Crop | Reference | Correlation coefficients | | | | |
|---|---|---|---|---|---|---|
| | | $EC_{iw}$ | $\pi^1$ | $EC_{dw}$ | Ave. $EC_e$ | $\pi'^2$ |
| Sudan grass | Bower *et al.* (1970) | 0.19 | 0.57 | 0.88 | 0.84 | - |
| Tall fescue | Bower *et al.* (1970) | 0.50 | 0.85 | 0.81 | 0.99 | - |
| Alfalfa | Bouwer *et al.* (1969) | 0.31 | 0.84 | 0.89 | 0.98 | - |
| Alfalfa | Ingvalson *et al.* (1976) | 0.53 | 0.71 | 0.80 | 0.78 | 0.89 |

1 As calculated with Eq [2].
2 From time and space integrated *in situ* soil water salinity values.

drainage water salinity ($r^2$ = 0.80) than with irrigation water salinity ($r^2$ = 0.53). Correlation was best with time- and depth-integrated salinity ($r^2$ = 0.89) though correlation with average rootzone salinity ($r^2$ = 0.78) and water-uptake- weighted salinity ($r^2$ = 0.71) were reasonably good. Similar results were obtained when the data of Bower *et al.* (1969; 1970) were evaluated in terms of the appropriateness of various indices of salinity for assessing crop yield. The results are given in Table 24.

Before the likelihood of a salinity hazard resulting from irrigating with saline waters can be exactly assessed, taking into account the effects of leaching fraction, irrigation frequency, soil properties, etc., it is necessary to be able to relate crop response quantitatively to time and space varying $\pi$, $\tau$ and $\phi$. At present, no completely satisfactory index of water salinity or potential which includes all the related environmental stresses and irrigation management effects exists with which to judge water suitability for irrigation. For this reason, any salinity hazard assessment of an irrigation water can only be an approximation at best.

Steady-state conditions do not occur under many of the situations encountered in irrigated agriculture. While steady-state conditions may result in the production of perennial crops in arid regions, rainfall and changes of crop over time generally prevent steady-state conditions for annual crops, especially if grown in sub-humid climates. Complicated dynamic types of models will be required (to evaluate the suitabilities of waters for irrigation) to take into account all the various climatic crop, soil, water, atmosphere, irrigation management, and time related variables influencing total water potential and the other stresses. Comprehensive models of the type described by Nimah and Hanks (1973), Bresler (1987), Dutt *et al.* (1972), and Letey, Knapp and Solomon (1990), but more inclusive than these, will be needed for such evaluations. At present, more information on how crops respond to time- and space-varying salinity are needed before such comprehensive models can be fully utilized (justified) to predict crop response to irrigation with saline waters. This is true no matter how sophisticated the model is in calculating the content of soil water and its salinity under dynamic conditions. Yet a need exists now for some reasonable method for evaluating the salinity hazards of irrigation waters and, therefore, some reasonable approach must be adopted based on best available practical information and logic. Because of the good correlations, the results of the conceptual modelling study of Rhoades and Merrill (FAO 1976) and the limitations in knowledge of crop response to time- and depth-varying matric- and osmotic-stresses and practical models to predict and relate these factors, the use of depth-weighted and water-uptake weighted salinities is deemed appropriate for judging the suitabilities of saline waters for irrigation.

## METHODS AND MODELS FOR ASSESSING THE SUITABILITY OF SALINE WATER FOR IRRIGATION AND CROP PRODUCTION

### Use of the Watsuit Computer Model[1]

Conceptually, a transient state (dynamic) model would be preferred for assessing water suitability for irrigation because it could incorporate the specific influences of the many variables that can influence crop response to salinity, including climate, soil properties, water chemistry, irrigation and other management practices (Rhoades 1972). However, as discussed earlier, many of the inputs required for use of such models are generally not available for most practical applications and there is much uncertainty about how to relate crop response to time- and space-varying salinity and water potential, such as might be predicted with such models. For these reasons, the practicality and value of such complex models may be less appropriate under some circumstances than a conceptually inferior model for the practical purpose of assessing suitability of saline water for irrigation. Furthermore, the steady-state composition likely represents the worst-case situation (maximum build-up of salinity and sodicity) that would result from irrigation with the water. For the above reasons, a relatively simple steady-state model called Watsuit is described to judge water suitability for irrigation under one meaningful, reference condition, i.e. steady-state, the likely worst-case situation that could result from its use.

The concentrations of the major cations and anions in the soil water within an irrigated rootzone are predicted at equilibrium by Watsuit as a function of irrigation water composition, leaching fraction, soil $CaCO_3$ presence or absence, and several alternative amendment treatments. Also predicted are $SAR_{sw}$, pH and $EC_{sw}$ at the soil surface. Watsuit accounts for the precipitation and dissolution of important soil minerals (primarily $CaCO_3$ and $CaSO_4 \bullet 2H_2O$) on the composition of the soil solution within the rootzone. As discussed earlier, salt precipitation and mineral weathering can affect the levels of soil water salinity depending upon irrigation water composition and leaching fraction. The relative magnitude of such effects can be evaluated using Watsuit calculations. Details about the assumptions and relations that comprise this model are given in Rhoades (1972; 1977; 1984a; 1987b; 1988a) and Oster and Rhoades (1990).

Prognoses of water suitability for irrigation are made by comparing predicted soil water compositions, salinities and sodicities obtained from Watsuit against standards of acceptance with respect to salinity, permeability and crusting and toxicity criteria. The effect of irrigation frequency is indirectly taken into account by altering the index of salinity used to judge the potential salinity hazard depending on the type of irrigation management to be employed, as described later and for the reasons given earlier. The effect of salinity on crop yield under frequent irrigation management (i.e. when little matric stress exists) is evaluated using either water-uptake-weighted EC or $\pi$ (i.e. $\overline{EC}$ or $\bar{\pi}$) or upper profile EC. For infrequent irrigation (i.e. conventional management where significant matric stress occurs over the irrigation interval), average profile EC is used to judge the likelihood of a salinity problem. To assess toxicity problems, specific solute concentrations of potential toxicants ($Cl^-$, B) are used in place of EC. To assess nutritional adequacy or balance, concentrations of Ca ($\geq$ 2 $mmol_c$/l) and Ca/Mg ratios ($\geq$ 1) are used as criteria (standards). To evaluate potential permeability and crusting problems, soil surface SAR and the EC of the infiltrating water are compared against appropriate SAR (or ESP) - $EC_{iw}$ threshold relations for the soils of concern (Figure

[1] A floppy disk of the model is available on request from FAO or from the senior author.

2 may be used in the absence of such specific information). The benefits of amendments are evaluated from examination of the predicted compositions with and without treatment.

Soil salinity is judged a likely problem if the predicted appropriate index of rootzone salinity exceeds the tolerance of the crops to be grown. The salt tolerances for different plant species are given in Tables 13 to 15. If some yield reduction can be tolerated, a higher salinity (or toxicant concentration) tolerance level is used, as appropriate, in place of the threshold levels. Since the salt tolerance tables are expressed in terms of $EC_e$, while the Watsuit predictions of EC, $\overline{C}$ and $\overline{\pi}$ are given in terms of soil water at field capacity, some conversions in units are required before acceptability is evaluated. These various measures of salinity can be reasonably put on an equivalent basis for comparison using the relations:

$$EC_e \approx \frac{1}{2} EC_{sw} \tag{4}$$

$$\overline{EC} \approx 0.1\ \overline{C} \tag{5}$$

$$\overline{\pi} \approx 0.39\ \overline{EC} \tag{6}$$

where EC is in dS/m, $\overline{C}$ is in $mmol_c/l$ and $\overline{\pi}$ is in kPa.

Toxicity problems are evaluated analogously, using calculated solute concentration and toxicity thresholds given in Tables 17 to 21.

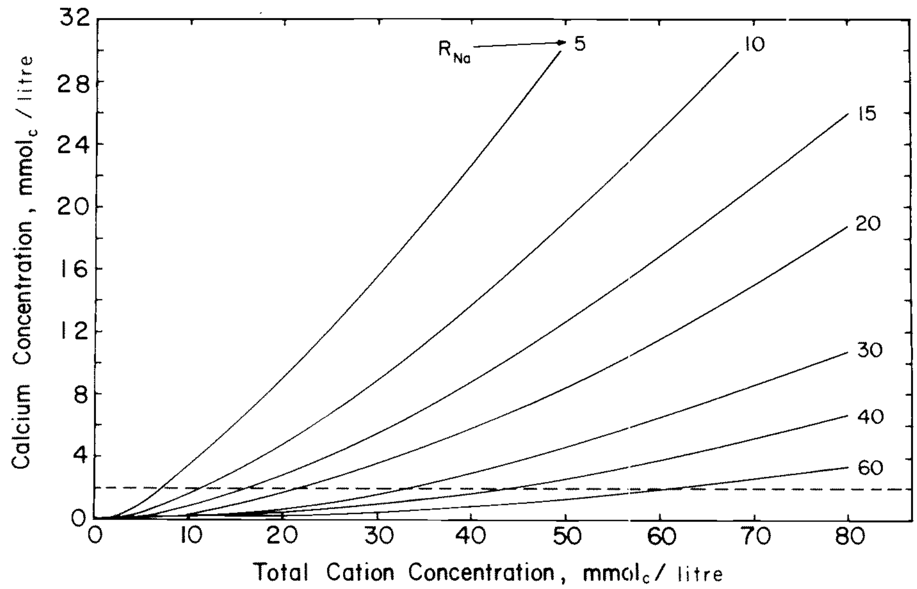
Soil permeability and crusting are judged likely problems if the combination of predicted near-surface SAR and pH and irrigation water EC are expected to result in significant aggregate slaking, clay swelling and dispersion using relevant specific threshold guidelines of soil permeability and crusting for the specific soils in question, or Figure 2 by default. The benefits of soil and water amendments on water suitability, as regards permeability and tilth problems, are evaluated based on their effects on SAR, pH and EC.

The chemistry part of the model is also of value for assessing the nutritional adequacy of calcium, because it can predict the concentrations and distributions of Ca and Mg, as well as SAR, and EC within the rootzone. This is important because whether or not a sodic soil condition upsets crop nutrition is also influenced by the total salt concentration (Bernstein 1974; Rhoades 1982). If a soil is saline, or if the Ca concentration exceeds about 2 $mmol_c/l$, even a high level of SAR will have little harmful nutritional effect on most crops, as distinguishable from that of salinity, and can be ignored. Thus the major concern, with respect to sodium-toxicity or calcium-nutrition problems, occurs under non-saline, sodic and alkaline pH conditions where Na concentration is high, Ca concentration is low ($\leq$ 2 $mmol_c/l$) and/or where the Ca/Mg ratio is less than about 1 (Lagerwerff and Holland 1960).

Generally, chloride and sodium toxicities are only of concern with woody plants. The most chloride-sensitive plants may be injured when chloride concentration in the soil saturation extract exceeds 5 or 10 $mmol_c/l$, while the most tolerant woody plants are damaged only at a chloride concentration of about 30 $mmol_c/l$ or greater (Bernstein 1974; 1980).

No procedure is given to evaluate sodium toxicity *per se* for field, forage and vegetable crops, in spite of the fact that sodicity tolerances have conventionally been given for them in terms of exchangeable sodium percentage (Pearson 1960; Bernstein 1974). The crop

FIGURE 7
Relationship between calcium concentration, total cation concentration and sodium adsorption ratio




responses associated with sodicity levels in these and similar studies were likely a result of the way the experiments were carried out. An examination of the experimental data (Bernstein and Pearson 1956; Pearson and Bernstein 1958) shows that the yield reduction ascribed to toxic levels of exchangeable sodium only occurred when either Ca was in the deficient range (< about 1-2 $mmol_c/l$) or the crop's salt tolerance threshold value *per se* was exceeded. Figure 7 (after Rhoades 1982) clearly shows that SAR at low levels of salinity cannot be increased without simultaneously reducing Ca concentration to nutritionally inadequate levels, or achieve high values of SAR while keeping Ca nutritionally adequate (> 1-2 $mmol_c/l$) without also increasing total salinity to high levels. Sodium toxicity is apparently real for woody plants which do show sodium toxicity symptoms after sufficient accumulation in the plant tissue has occurred. Tolerance levels for these crops are given by Bernstein (1974).

Plants respond primarily to the boron concentration of the soil water rather than to the amount of absorbed B (Hatcher *et al.* 1959; Bingham *et al.* 1981). Boron is adsorbed by soil constituents and an equilibrium exists between the amounts in solution and in the absorbed state. In the long run, boron concentrates in the soil water, just as non-reactive solutes do. Obviously, for some transitional period of time dependent upon soil properties, amount of irrigation water applied, leaching fraction, and B concentration of the irrigation water, boron concentration in the soil water will be less than that predicted. The time necessary to achieve this steady-state is usually less than 10 years.

### *Description of input requirements and operation of Watsuit Model*

Annual (or longer) averages of irrigation water composition (corrected for rainfall dilution) and leaching fraction are required as inputs. Ideally, the input composition of the irrigation water should contain equal concentrations ($mmol_c/l$ basis) of cations and anions. If not, they must be made equal. This is best done by someone knowledgeable of the chemistry of the water in question and the procedures used in its analysis and any likely errors therein. If the input charge concentrations of the cations and anions are not made equal, a "charge-balance" subroutine in the model adjusts the input concentrations of the solutes to satisfy equivalency requirements in this regard, as explained later. Leaching fraction choices include 0.05, 0.1, 0.2, 0.3 and 0.4; amendment choices include gypsum and sulphuric acid. Depth distributions of plant water uptake and $CO_2$ partial pressure are assumed and fixed within the program. Saturation with respect to soil lime may be chosen, or not, to account for the potential effects of dissolution of soil lime, or soil silicates, or both, as appropriate to the soil in question. The model runs on standard personal computers. With 16 byte technology, the calculation time for one leaching fraction and amendment choice is approximately five minutes; with 32 byte technology, it is about 30 seconds.

TABLE 25
**Terminal display during Watsuit start-up**

```
Wish to send output to (D)isk or (S)creen

To print results in screen mode, hit: control P

SATURATE WITH CACO3?   Y

CASE ID

_______________________

PORT

ENTER DELIMITED BY COMMAS:
  CA, MG, NA, K, CL, ALK and SO4

WHICH AMENDMENTS?

  (B) H2SO4?
  (C) 1 CASO4?
  (D) 20 CASO4?

WHICH LEACHING FRACTIONS TO ACCEPT?

  .05?
  .10?
  .20?
  .30?
  .40?
```

Table 25 shows the monitor display during data entry. The following selections require responses and appropriate entries:

- Are the results to be printed, stored on disk, or displayed on screen?
- Is the soil-lime saturation assumption to be accepted or rejected?
- How is the case to be identified?
- What is the ionic composition of the water in units of $mmol_c/l$ (= meq/l)?
- Which amendments and leaching fractions should be included?

Amendment choices include the following: (a) addition of sulphuric acid to the irrigation water to replace 90 percent of the alkalinity with sulphate (chemical equivalent basis), (b) addition of gypsum to the irrigation water in amount equivalent to 1 or more $mmol_c/l$ of $CaSO_4$ to simulate water- or top-dressed soil-treatments with gypsum, or (c) incorporation of gypsum in the soil in an amount that will add the equivalent of 20 $mmol_c/l$ of $Ca^{++}$ and $SO_4^{--}$ to the infiltrating water to simulate soil-incorporated treatment with a substantial amount of gypsum. All amendments can be chosen in the same computer run. No amendment is the default condition: it is always run. The amendment routines have less utility for highly saline waters because permeability is less of a problem and their treatment is less practical than low salinity waters.

The composition of the soil water at equilibrium is calculated (predicted) in terms of $Ca^{++}$, $Mg^{++}$, $Na^{+}$, $CO_3^{--}$, $HCO_3^{-}$, $Cl^{-}$, $SO_4^{--}$, pH, EC, as are the water-uptake-weighted chloride concentration and osmotic potential, for each of five relative soil depths--the soil surface, 1/4, 1/2, 3/4, and full depth of the rootzone. Average soil water EC and SAR

TABLE 26
**Terminal display of predicted soil water composition resulting from irrigation with Pecos well water at leaching fractions of 0.1, 0.2, 0.3 and 0.4**

---- WATER SUITABILITY DETERMINATION MODEL ----

Output file: WATOUT

INPUT

CA= 11.60 MG= 9.30 NA= 19.40 K= .40
CL= 27.40 ALK= 4.10 SO4= 9.20
**************

**** CASE: pecos we *** (A) UNTREATED ***
**** LF TREATMENT: .10

| DEPTH | LF | 1/LF | CA | MG | NA+K | CL | CO3 | HCO3 | SO4 |
|---|---|---|---|---|---|---|---|---|---|
| 0 | 1.00 | 1.00 | 9.11 | 9.30 | 19.80 | 27.40 | .44 | 1.16 | 9.20 |
| 1 | .64 | 1.56 | 14.92 | 14.53 | 30.94 | 42.81 | .44 | 2.77 | 14.37 |
| 2 | .37 | 2.70 | 25.11 | 25.14 | 53.51 | 74.05 | .44 | 4.41 | 24.86 |
| 3 | .19 | 5.26 | 45.11 | 48.95 | 104.21 | 144.21 | .44 | 5.20 | 48.42 |
| 4 | .10 | 10.00 | 60.54 | 93.00 | 198.00 | 274.00 | .46 | 6.45 | 70.64 |

| DEPTH | PH | CA/MG | SUM CAT. | EC | SAR | MGSITE | LIME | GYP |
|---|---|---|---|---|---|---|---|---|
| 0 | 7.93 | .979 | 38.21 | 3.77 | 6.40 | .00 | 2.49 | .00 |
| 1 | 7.42 | 1.027 | 60.39 | 5.89 | 7.90 | .00 | 3.20 | .00 |
| 2 | 7.11 | .999 | 103.76 | 9.77 | 10.46 | .00 | 6.24 | .00 |
| 3 | 6.93 | .922 | 198.27 | 18.10 | 14.89 | .00 | 15.94 | .00 |
| 4 | 6.84 | .651 | 351.54 | 30.34 | 22.14 | .00 | 34.10 | 21.36 |

**** CASE: Pecos we *** (A) UNTREATED ***
**** LF TREATMENT: .20

| DEPTH | LF | 1/LF | CA | MG | NA+K | CL | CO3 | HCO3 | SO4 |
|---|---|---|---|---|---|---|---|---|---|
| 0 | 1.00 | 1.00 | 9.11 | 9.30 | 19.80 | 27.40 | .44 | 1.16 | 9.20 |
| 1 | .68 | 1.47 | 14.25 | 13.68 | 29.12 | 40.29 | .44 | 2.78 | 13.53 |
| 2 | .44 | 2.27 | 21.94 | 21.14 | 45.00 | 62.27 | .43 | 4.46 | 20.91 |
| 3 | .28 | 3.57 | 32.52 | 33.21 | 70.71 | 97.86 | .44 | 5.30 | 32.86 |
| 4 | .20 | 5.00 | 43.85 | 46.50 | 99.00 | 137.00 | .44 | 5.91 | 46.00 |

| DEPTH | PH | CA/MG | SUM CAT. | EC | SAR | MGSITE | LIME | GYP |
|---|---|---|---|---|---|---|---|---|
| 0 | 7.93 | .979 | 38.21 | 3.77 | 6.40 | .00 | 2.49 | .00 |
| 1 | 7.43 | 1.042 | 57.04 | 5.57 | 7.64 | .00 | 2.81 | .00 |
| 2 | 7.12 | 1.038 | 88.08 | 8.43 | 9.50 | .00 | 4.42 | .00 |
| 3 | 6.98 | .979 | 136.45 | 12.75 | 12.09 | .00 | 8.91 | .00 |
| 4 | 6.87 | .943 | 189.35 | 17.44 | 14.43 | .00 | 14.15 | .00 |

**** CASE: Pecos we *** (A) UNTREATED ***
**** LF TREATMENT: .30

| DEPTH | LF | 1/LF | CA | MG | NA+K | CL | CO3 | HCO3 | SO4 |
|---|---|---|---|---|---|---|---|---|---|
| 0 | 1.00 | 1.00 | 9.11 | 9.30 | 19.80 | 27.40 | .44 | 1.16 | 9.20 |
| 1 | .72 | 1.39 | 13.65 | 12.92 | 27.50 | 38.06 | .44 | 2.80 | 12.78 |
| 2 | .51 | 1.96 | 19.65 | 18.24 | 38.82 | 53.73 | .43 | 4.51 | 18.04 |
| 3 | .37 | 2.70 | 26.08 | 25.14 | 53.51 | 74.05 | .43 | 5.38 | 24.86 |
| 4 | .30 | 3.33 | 31.46 | 31.00 | 66.00 | 91.33 | .43 | 6.02 | 30.67 |

| DEPTH | PH | CA/MG | SUM CAT. | EC | SAR | MGSITE | LIME | GYP |
|---|---|---|---|---|---|---|---|---|
| 0 | 7.93 | .979 | 38.21 | 3.77 | 6.40 | .00 | 2.49 | .00 |
| 1 | 7.43 | 1.057 | 54.07 | 5.28 | 7.39 | .00 | 2.46 | .00 |
| 2 | 7.14 | 1.077 | 76.71 | 7.36 | 8.74 | .00 | 3.10 | .00 |
| 3 | 7.01 | 1.038 | 104.73 | 9.85 | 10.36 | .00 | 5.27 | .00 |
| 4 | 6.92 | 1.015 | 128.46 | 12.01 | 11.57 | .00 | 7.21 | .00 |

**** CASE: Pecos we *** (A) UNTREATED ***
**** LF TREATMENT: .40

| DEPTH | LF | 1/LF | CA | MG | NA+K | CL | CO3 | HCO3 | SO4 |
|---|---|---|---|---|---|---|---|---|---|
| 0 | 1.00 | 1.00 | 9.11 | 9.30 | 19.80 | 27.40 | .44 | 1.16 | 9.20 |
| 1 | .76 | 1.32 | 13.12 | 12.24 | 26.05 | 36.05 | .44 | 2.82 | 12.11 |
| 2 | .58 | 1.72 | 17.91 | 16.03 | 34.14 | 47.24 | .43 | 4.55 | 15.86 |
| 3 | .46 | 2.17 | 22.19 | 20.22 | 43.04 | 59.57 | .43 | 5.45 | 20.00 |
| 4 | .40 | 2.50 | 25.29 | 23.25 | 49.50 | 68.50 | .43 | 6.11 | 23.00 |

| DEPTH | PH | CA/MG | SUM CAT. | EC | SAR | MGSITE | LIME | GYP |
|---|---|---|---|---|---|---|---|---|
| 0 | 7.93 | .979 | 38.21 | 3.77 | 6.40 | .00 | 2.49 | .00 |
| 1 | 7.44 | 1.072 | 51.41 | 5.02 | 7.17 | .00 | 2.14 | .00 |
| 2 | 7.15 | 1.117 | 68.08 | 6.60 | 8.12 | .00 | 2.09 | .00 |
| 3 | 7.03 | 1.097 | 85.45 | 8.17 | 9.16 | .00 | 3.03 | .00 |
| 4 | 6.95 | 1.088 | 98.04 | 9.34 | 9.84 | .00 | 3.71 | .00 |

are also calculated for both the whole rootzone and upper one-half of the rootzone. The EC and SAR of the soil water at the top of the rootzone are given in the printout to aid in judging the likelihood of permeability and tilth problems.

### *Example of use of the Watsuit Model*

The predicted steady-state compositions of the soil solution at the soil surface and through the rootzone resulting from irrigation with untreated Pecos well water are given in Table 26 for LF values of 0.1 to 0.4. Also given are the calculated Ca/Mg and SAR ratios, EC values, etc. and, in this case, the loss in applied salt (in $mmol_c/l$) due to the precipitation of soil lime and, in one case, gypsum. The increases in ion concentrations, EC and SAR that occur with depth are due to increasing values of 1/LF with depth. The decrease in pH with depth reflects the assumed increase in $pCO_2$ with depth.

The summary data for the different leaching fractions, including average profile EC, SAR and chloride concentration, upper profile EC, SAR, and chloride concentration, and water-uptake-weighted salinity in concentration units of $mmol_c/l$ and in osmotic potential units of kPa($\overline{PI}$), are given in Table 27 and expressed on a field capacity soil water basis. The predicted average rootzone salinities (AVG.EC) range from 6.6 to 12.7 dS/m. On a saturation extract basis these values are about 1/2 those at field capacity, i.e. 3.3 to 6.3 dS/m.

TABLE 27
Terminal display of summary data for untreated Pecos well water, as calculated by Watsuit

**** CASE: Pecos we *** (A) UNTREATED ***

| LF TF. | AVG.EC | UP.EC | AVG.SAR | UP.SAR | AVG.CL | UP.CL | C' | $\overline{PI}$' |
|---|---|---|---|---|---|---|---|---|
| .10 | 12.71 | 6.33 | 11.88 | 8.16 | 102.94 | 46.77 | 96.90 | 3.49 |
| .20 | 9.34 | 5.83 | 9.91 | 7.79 | 70.66 | 42.57 | 77.40 | 2.79 |
| .30 | 7.59 | 5.42 | 8.87 | 7.48 | 56.30 | 39.31 | 66.79 | 2.40 |
| .40 | 6.59 | 5.10 | 8.14 | 7.21 | 47.70 | 36.69 | 59.78 | 2.15 |

SUR.EC= 3.773 SUR.SAR= 6.395

*** PROGRAM OPTIONS USED +++
NO MGCOS PPT. CONSIDERED.
CACO3 FORCED TO SATURATION

By comparison of these latter values with those given in the salt tolerance data of Tables 13 to 21, it is concluded that salinity would not be a significant problem with use of this water for the irrigation of most field crops (provided plant stand is first established), but it could be for some salt sensitive crops such as the lettuce, beans, etc. Chloride levels would be excessive for sensitive woody perennial plants (see chloride tolerance Tables 20 and 21). Calcium concentrations are $\geq$ 2 $mmol_c/l$ and relative Ca/Mg proportions are $\geq$ 1/1, hence calcium should be nutritionally adequate for most crops. The levels of SAR relative to EC and pH at the soil surface (Table 27) and throughout the rootzone (Table 26) are well within the unlikely problem area of Figure 2; hence no problems related to infiltration and reduced hydraulic conductivities are anticipated. However, rainfall would increase the likelihood of this latter problem because the resulting reduction in soil solution EC in the topsoil would increase the likelihood of aggregate slaking and the dispersion and swelling of soil clays (Shainberg and Letey 1984). Application of gypsum to the soil surface, or injection into the irrigation water would reduce these hazards. Such near-surface effects can also often be overcome by tillage and other cultural techniques.

TABLE 28
**Water and calcium balance within the rootzone after irrigation with Pecos river water[1] at two leaching fractions calculated using Watsuit (after Oster and Rhoades 1990)**

| Leaching fraction (1) | Rootzone depth interval (2) | Volume of leachate (3) | Calcium concentration in leachate ($mmol_c/l$) (4) | Mass of calcium in leachate[2] ($mmol_c/l$) (5) | Calcium gain (+) or loss (-) within the depth interval[3] ($mmol_c/l$) (6) |
|---|---|---|---|---|---|
| 0.1 | 1 | 71.1 | 24.5 | 1 740 | (-)40 |
| | 2 | 41.1 | 33.0 | 1 354 | (+)386 |
| | 3 | 21.1 | 33.1 | 698 | (+)656 |
| | 4 | 11.1 | 32.8 | 364 | (+)334 |
| 0.3 | 1 | 102.9 | 22.1 | 2 273 | (-)90 |
| | 2 | 73.9 | 31.5 | 2 298 | (-)25 |
| | 3 | 52.9 | 33.4 | 1 764 | (+)534 |
| | 4 | 42.9 | 33.7 | 1 440 | (+)324 |

1 The chemical composition of this water is as follows, in $mmol_c/l$: 11.38 (NA), 0.08 (K), 16.98 (Ca), 9.07 (Mg), 3.11 ($HCO_3$), 12.13 (Cl) and 22.39 ($SO_4$). The EC is 3.3 dS/m.
Rootzone depth is divided into four quarters, with 1 representing the top quarter and 4 the bottom
2 Mass of Ca infiltrated equalled 1700 and 2186 $mmol_c/l$ at leaching fractions of 0.2 and 0.3 respectively.
3 The differences in Ca mass entering and leaving the rootzone depth intervals.

Recall that the Watsuit predictions reflect the likely worst-case condition (i.e. maximum build-up of salt, such as would occur at steady-state). With significant rainfall, change to crops with lower evapotranspiration rates, with extra water given during pre-sowing irrigations, etc., more leaching would occur than was assumed in the calculations and, hence, soil salinity in the rootzone would likely be lower than predicted. Also, effective levels of soil salinity experienced by the roots would be lower if high frequency irrigation were used. For such cases, the water-uptake-weighted or upper EC values predicted by Watsuit should be used as the index of salinity to compare with crop tolerance threshold values. For such irrigation management, one would conclude that even more salt-sensitive crops could be grown with Pecos River water, such as maize and beans, etc.

The data in Table 28 illustrate the use of Watsuit to predict the effects of leaching fraction on the loss, or gain, of Ca salts in the rootzone of a crop irrigated with Pecos River water to steady-state (other data of this type are given in Oster and Rhoades 1977). This water is gypsiferous (see Table 28): the Ca millimolar concentration, 8.5 $mmol_c/l$, is equivalent to 34% of the total millimolar concentration of cations, and the sulphate millimolar concentration, 11.2 mmol/l, is equivalent to 43% of the total millimolar concentration of anions. The volumes of leachate leaving each quarter depth of the rootzone (Col. 3, Table 28) were calculated assuming the following: (i) 100 units of plant water uptake, (ii) leaching fractions of 0.3 and 0.1 and corresponding units of applied water of 142.9 and 111.1, respectively and (iii) the assumed water uptake and $pCO_2$ depth distributions as described above. The concentrating effects due to the decreasing leachate volume with depth (i.e. due to plant water-uptake), and to a smaller extent due to the dissolution of soil lime, results in an increased Ca concentration (Col. 4) in the leachate from the second depth, as compared to that from the first depth, for both leaching fractions. However, the Ca concentrations at the third and fourth depths are about the same as at the second depth because gypsum and lime precipitation are largely counteracting the additional concentrating effects of water uptake by the plant in these lower depths. Consequently the mass of Ca in the leachate ($V*C_{ca}$; see Table 28, Col. 5) decreases with depth in all cases but one. A small increase occurs from depth one to two for the 0.3 leaching fraction. The loss of Ca (Col. 6) from the upper portion of the rootzone results from soil lime dissolution. Precipitation of soil lime and gypsum results in a gain of insoluble Ca within the lower portions of the rootzone. These results show that the amount of solids precipitating in the soil can be appreciable for such gypsiferous waters and can lower the effective soil water salinity that would otherwise result.

The preceding data illustrate how salt precipitation can effect soil salinity and how Watsuit can be used to predict effective soil water salinity and the degree or need for adjustment in this regard. For more examples see Oster and Rhoades (1977 and 1990). The use of Watsuit model predictions to assess the potential of using saline agricultural drainage waters for irrigation, is illustrated in more detail elsewhere (Rhoades 1977; 1984a; 1987b; 1988a; Oster and Rhoades 1990). The results of such evaluations leads to the conclusion that many agricultural drainage waters and shallow groundwaters found in irrigated lands are suitable for irrigation of selected crops and that their use could increase food production, lessen drainage disposal requirements and improve land and water resource use efficiency (Rhoades 1977; 1984b).

## Use of a Non-computer Version of Watsuit Model

### *Description of input requirements and operation*

A non-computer version of Watsuit can be used, where computer facilities are lacking, in an analogous way to "Watsuit" to predict the likelihood of soil water salinity-, sodicity- and toxicity-related problems resulting from irrigation under steady-state conditions. With this procedure, steady-state salinity, or solute concentration, is estimated by multiplying the EC (or solute concentration) of the irrigation water by a relative concentration factor, $F_c$, appropriate to the leaching fraction and depth in the rootzone. These factors are given in Tables 29 and 30. Figures 8 and 9 (after Rhoades 1982), which are the graphical equivalents of Tables 29 and 30, can be used in place of the tables.

These predictions are less accurate than those made with Watsuit and are more conservative because they do not take into account the effects of mineral precipitation-dissolution reactions, or ion-pair formation, on resultant soil water salinity and solute composition.

As discussed earlier, some reduction in soil salinity can be expected by calcite and gypsum precipitation if the irrigation water is high in Ca and $HCO_3$ or $SO_4$. However, corrections for loss of Ca, $HCO_3$ and $SO_4$ by precipitation of $CaCO_3$ and $CaSO_4 \cdot 2H_2O$ are usually not needed to assess properly the salinity hazard of typical saline irrigation waters for LF values of $\geq 0.2$, given the other uncertainties involved in the assessment. But for very saline gypsiferous waters, correction for such loss is advised. Ideally, this correction should be made (automatically) using Watsuit. In the absence of Watsuit, it can be made using the graphical methods of Suarez (1982) or the empirical relationships of Oster and Rhoades (1977). Only the former method is described herein, because it is based on more fundamental relationships which likely provide greater flexibility of use.

The following procedure is used to calculate Ca, $HCO_3$ and $SO_4$ losses (or gains) and their final equilibrium concentrations in the soil solution resulting from irrigation under

FIGURE 8
Relationships between average rootzone salinity (saturation extract basis), EC of irrigation water and LF for conditions of conventional irrigation management

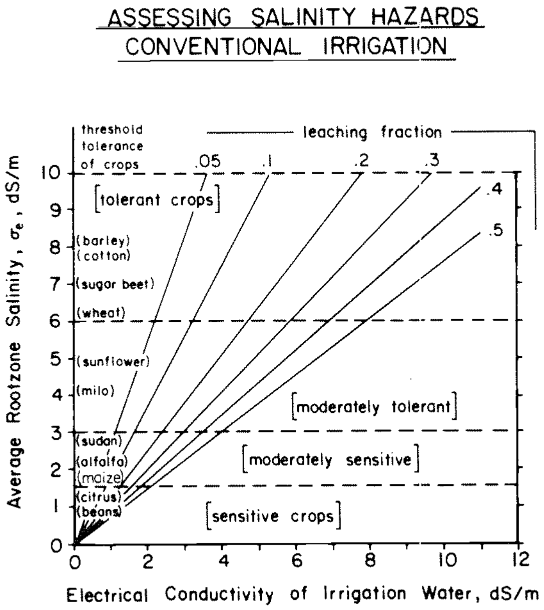



FIGURE 9
Relationships between water-uptake-weighted salinity (saturation extract basis), EC of irrigation water and LF for conditions of high-frequency irrigation

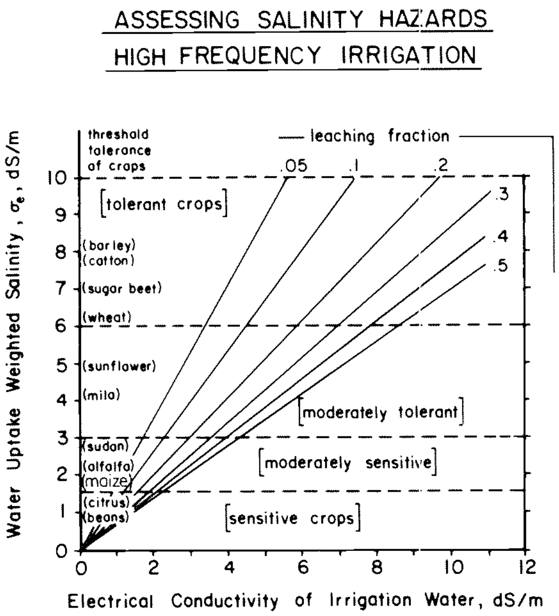


TABLE 29

**Relative solute concentrations of soil water (field capacity basis) compared to that of irrigation water ($F_c$ = $1/LF_a$) by depth in rootzone and leaching fraction[1]** (after Rhoades 1982)

| Rootzone depth in quarters | $V_{cu}$[2] | $F_c$ (= $1/LF_a$) | | | | | |
|---|---|---|---|---|---|---|---|
| | | Leaching fraction | | | | | |
| | | .05 | .10 | .20 | .30 | .40 | .50 |
| 0 | 0 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 1 | 40 | 1.61 | 1.56 | 1.47 | 1.39 | 1.32 | 1.25 |
| 2 | 70 | 3.03 | 2.70 | 2.27 | 1.96 | 1.72 | 1.54 |
| 3 | 90 | 7.14 | 5.26 | 3.57 | 2.70 | 2.17 | 1.82 |
| 4 | 100 | 20.00 | 10.00 | 5.00 | 3.33 | 2.50 | 2.00 |

1 Assuming 40:30:20:10 water uptake pattern in rootzone.
2 Accumulative percentage of consumptive use above this depth in rootzone.

TABLE 30

**Relative concentration or electrical conductivity of soil water (saturation paste extract basis) at steady-state compared to that of irrigation water ($\overline{F}_c$)** (after Rhoades 1982)

| Rootzone interval | $\overline{F}_c$ | | | | | |
|---|---|---|---|---|---|---|
| | Leaching fraction | | | | | |
| | 0.05 | 0.10 | 0.20 | 0.30 | 0.40 | 0.50 |
| | Linear average[1] | | | | | |
| Upper quarter | 0.65 | 0.64 | 0.62 | 0.60 | 0.58 | 0.56 |
| Whole rootzone | 2.79 | 1.88 | 1.29 | 1.03 | 0.87 | 0.77 |
| | Water uptake weighted[2] | | | | | |
| Whole rootzone | 1.79 | 1.35 | 1.03 | 0.87 | 0.77 | 0.70 |

1 Use for conventional irrigation management.
2 Use for high frequency irrigation management or where matric potential development between irrigations is insignificant.

steady-state conditions. First calculate the initial (without loss or gain) soil water concentration as ($Fc \cdot Ca_{iw}/2$), ($F_c \cdot HCO_{3,iw}$) and ($F_c \cdot SO_{4,iw}/2$), where $F_c$ is obtained from Tables 29 or 30 as appropriate to the depth or average depth in the rootzone being evaluated. The concentrations of divalent ions are divided by 2 to convert units from $mmol_c/l$ to mmol/l. Next, estimate the ionic strength of the soil water in this depth(s) from:

$$\mu = 0.0127\ (EC_{iw})\ (F_c) \qquad (7)$$

where $EC_{iw}$ is in dS/m.

Using $\mu$ and an appropriate estimate of $P_{CO2}$, obtain the appropriate scale factor to use for calculating Ca loss (or gain) in $CaCO_3$ controlled systems (i.e., for alkaline type waters where $HCO_3$ > Ca and $HCO_3$ > $SO_4$) from Table 31. The $P_{CO2}$ in the soil varies considerably and is a function of temperature, soil moisture content, soil texture, porosity, irrigation frequency, soil fertility and crop type among others. For surface soil, use $P_{CO2} = 10^{-3.5}$; for

TABLE 31

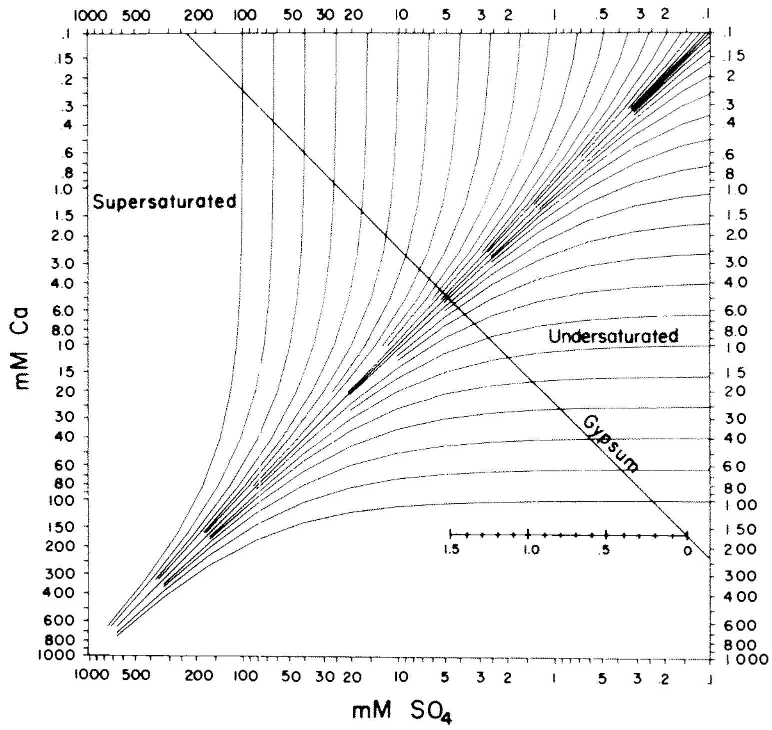
**Scale values to be used for determining solubility lines for Figures 10 and 11** (after Suarez 1982)

| $\mu$* | $10^{-3.5}$ | $10^{-3.0}$ | $10^{-2.5}$ | $10^{-2.2}$ | $10^{-2.0}$ | $10^{-1.5}$ | $10^{-1.2}$ | $10^{-1.0}$ | $10^{-0.5}$ | 100 | -log $(Ca^{++} \cdot SO_4^{2-}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| .001 | 0.09 | 0.59 | 1.09 | 1.39 | 1.59 | 2.09 | 2.39 | 2.59 | 3.09 | 3.59 | 0.12 |
| .002 | 0.14 | 0.64 | 1.14 | 1.44 | 1.64 | 2.14 | 2.44 | 2.64 | 3.14 | 3.64 | 0.17 |
| .005 | 0.20 | 0.70 | 1.20 | 1.50 | 1.70 | 2.20 | 2.50 | 2.70 | 3.20 | 3.70 | 0.26 |
| .007 | 0.23 | 0.73 | 1.23 | 1.53 | 1.73 | 2.23 | 2.53 | 2.73 | 3.23 | 3.73 | 0.30 |
| .010 | 0.27 | 0.77 | 1.27 | 1.57 | 1.77 | 2.27 | 2.57 | 2.77 | 3.27 | 3.77 | 0.35 |
| .020 | 0.35 | 0.85 | 1.35 | 1.65 | 1.85 | 2.35 | 2.65 | 2.85 | 3.35 | 3.85 | 0.47 |
| 0.03 | 0.42 | 0.92 | 1.42 | 1.72 | 1.92 | 2.42 | 2.72 | 2.92 | 3.42 | 3.92 | 0.55 |
| 0.04 | 0.46 | 0.96 | 1.45 | 1.76 | 1.96 | 2.45 | 2.76 | 2.96 | 3.46 | 3.96 | 0.61 |
| 0.05 | 0.50 | 1.00 | 1.50 | 1.80 | 2.00 | 2.50 | 2.80 | 3.00 | 3.50 | 4.00 | 0.66 |
| 0.07 | 0.57 | 1.07 | 1.57 | 1.87 | 2.07 | 2.57 | 2.87 | 3.07 | 3.57 | 4.07 | 0.75 |
| 0.10 | 0.64 | 1.14 | 1.64 | 1.94 | 2.14 | 2.64 | 2.94 | 3.14 | 3.64 | 4.14 | 0.84 |
| 0.15 | 0.72 | 1.22 | 1.72 | 2.02 | 2.22 | 2.72 | 3.02 | 3.22 | 3.72 | 4.22 | 0.95 |
| 0.20 | 0.78 | 1.28 | 1.78 | 2.08 | 2.28 | 2.78 | 3.08 | 3.28 | 3.78 | 4.28 | 1.03 |
| 0.25 | 0.83 | 1.33 | 1.83 | 2.13 | 2.33 | 2.83 | 3.13 | 3.33 | 3.83 | 4.33 | 1.09 |
| 0.30 | 0.87 | 1.37 | 1.87 | 2.17 | 2.37 | 2.87 | 3.17 | 3.37 | 3.87 | 4.37 | 1.14 |
| 0.40 | 0.92 | 1.42 | 1.92 | 2.22 | 2.42 | 2.92 | 3.22 | 3.42 | 3.92 | 4.42 | 1.22 |
| 0.50 | 0.96 | 1.46 | 1.96 | 2.26 | 2.46 | 2.96 | 3.26 | 3.46 | 3.96 | 4.46 | 1.27 |

1 $\mu$ 0.0127 $(c_i)F_c)$, where $F_c$ is the appropriate concentration factor for the leaching fraction (see Tables 26 and 27).

\+ Use the IAP value of $10^{-8.0}$ for $[Ca^{2+}][CO_3^{2-}]$ by adding 0.47 to the values determined above.

**FIGURE 10**
**Graphical solution for $CaCO_3$ solubility plotted for Ca and inorganic C alkalinity. Curved lines: precipitation-dissolution path, straight lines: equilibria**

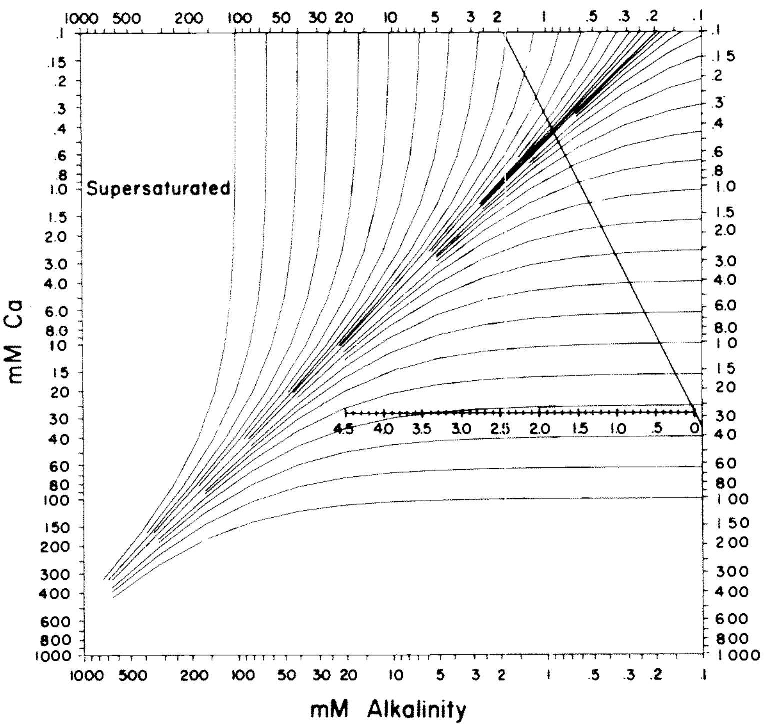



the lower rootzone, use $P_{CO_2}$ values of 0.03 and 0.01 for clay and sandy soils respectively, in the absence of more specific information.

Locate this scale factor in Figure 10 (after Suarez 1982) and draw a line parallel to the one shown (the one which crosses the curved lines). Now plot the values of ($F_c \cdot Ca_{iw}/2$) and ($F_c \cdot HCO_{3,iw}$) to locate the initial point which represents the Ca and $HCO_3$ concentrations in the soil water before reaction (i.e. loss or gain in solute mass in order to come to equilibrium with $CaCO_3$ at that $P_{CO_2}$ value). Next move this point parallel with the closest curved line toward the drawn straight line. The moving point gives the concentrations (in mmol/l) of Ca and $HCO_3$ that occur as the water equilibrates (losses or gains in concentration). The equilibrium concentrations ($Ca_e$ and $HCO_{3,e}$) are those corresponding to the intersection of the point with the drawn straight line. The loss (or gain) in Ca concentration is equal to the difference $[(Ca_{iw} \cdot F_c)/2 - Ca_e]$. The corresponding loss (or gain) in EC (dS/m) is equal to the product of 0.2 times this difference. The factor 0.2 corrects for the conversation between mmol/l and $mmol_c$/l and between $mmol_c$/l and EC (dS/m).

For gypsiferous systems, an analogous procedure to that described above for $CaCO_3$ systems is used to calculate Ca and $SO_4$ losses (or gains) and final equilibrium concentrations in soil solutions under steady-state conditions. In this case, the scale factor is first obtained, as before, from Table 31 corresponding to the value of $\mu$ (as calculated by Eq. 7). Then draw a line through the scale factor parallel to the straight line shown in Figure 11. The values of ($F_c \cdot Ca/2$) and ($F_c \cdot SO_4/2$) are plotted on this figure to locate the initial (pre-equilibration)

FIGURE 11
Graphical solution for gypsum solubility, plotted for Ca and $SO_4$. Curved lines represent precipitation-dissolution path, straight line equilibria (after Suarez 1982)




concentrations at that soil depth. This point is moved parallel to the closest curve toward the drawn straight line. The values of Ca and $SO_4$ corresponding to the intersection of the point and straight line are their equilibrium concentrations (in mmol/l) at steady-state in a gypsum-controlled system, $Ca_c$ and $SO_{4c}$, respectively. The loss (or gain) in salinity ($EC_{sw}$ basis) is equal to 0.2 times $[(Ca_{iw} \cdot F_c) - Ca_c]$.

Theoretically, systems in simultaneous equilibrium with $CaSO_4 \cdot 2H_2O$ and $CaCO_3$, require the use of both Figures 10 and 11 and successive iteration to determine final concentrations of Ca, $HCO_3$ and $SO_4$. The initial values of Ca and $HCO_3$ are first obtained from Figure 10. The Ca and $SO_4$ concentrations, corrected for gypsum precipitation, are next calculated from Figure 11 using Ca determined from Figure 10 and $SO_4$ initialized as $(SO_{4iw} \cdot F_c/2)$. This process is repeated successively until consistent values of Ca are obtained from both figures. These calculations can also be corrected for ion-pair effects, if desired, using relationships developed by Suarez (1982). However, when such refinement becomes necessary, it is far simpler, as well as more accurate, and advisable to use Watsuit in place of these non-computer methods.

For saline waters, especially given the uncertainty of the precise threshold levels of $SAR_{sw}$ and $EC_{iw}$ for different soils, the SAR and EC of the irrigation water are taken as generally suitable estimates of the levels resulting in the surface soil for purposes of assessing the permeability and tilth hazard. However, for special cases of highly sodic waters (high levels of SAR and bicarbonate, but relatively low levels of EC), the adjusted SAR value should be used in place of $SAR_{iw}$, as follows after Suarez (1981; 1982) and Jurinak and Suarez (1990):

$$adj\ SAR = \frac{Na_{iw}\ F_c}{\sqrt{(Mg_{iw}\ F_c + 2Ca_e)\ /\ 2}} \qquad (8)$$

where $Ca_e$ is the equilibrium concentration for the $CaCO_3$ (or $CaSO_4$) system as calculated using the above-described method, $Na_{iw}$ and $Mg_{iw}$ are concentrations ($mmol_c$/l basis) of Na and Mg, respectively, in the irrigation water, and $F_c$ is the concentration factor appropriate to the leaching fraction and soil depth (Tables 29 and 30). For calculating adj SAR for purposes of assessing soil surface permeability problems, use the value 1.0 for $F_c$.

The effects of amendment treatments on the suitability of sodic, saline irrigation water can be judged by first simulating their effects on the composition of the water and then calculating $Ca_e$ and adj. SAR values as described above. The potential benefit of treating the irrigation water and soil with gypsum is simulated by increasing its Ca concentration by 2 and 18 $mmol_c$/l, respectively (before the process of calculating concentrations at equilibrium is begun). The potential benefit of treating the irrigation water with sulphuric acid can be simulating by assuming the neutralization (reduction) of 90 percent of the waters' initial carbonate plus bicarbonate (alkalinity) concentration ($mmol_c$/l basis) with an equivalent increase in its $SO_4$ concentration. Then the calculations of $Ca_e$, adj. SAR, etc. proceed as described previously.

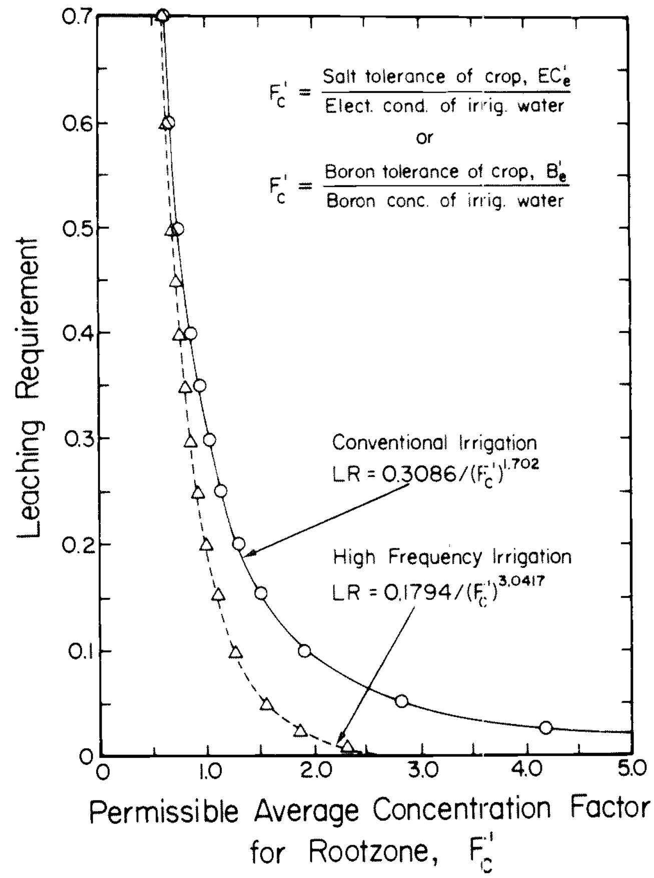
The assessment of salinity, permeability, toxicity or deficiency problems using the values of salinity, adj SAR, and $Ca_e$ are made analogously to that described for Watsuit. Salinity hazard is judged by comparison to plant tolerance values, permeability hazard with reference to threshold adj. $SAR_{iw}$ and $EC_{iw}$ values, and Ca adequacy by reference to critical $Ca_e$ values ($\geq$ 2 $mmol_c$/l) and cation ratios (Ca/Mg $\geq$ 1; Na/Ca $\leq$ 20), etc.

### *Example of use of non-computer method*

Use of Table 30 and the non-computer method to assess soil salinity are illustrated with the following example. For the Pecos River water with an $EC_{iw}$ of 3.8 dS/m and a leaching fraction of 0.10 with conventional irrigation frequency, average rootzone salinity ($EC_e$ basis) at steady-state is predicted to be 7.1 dS/m (1.88 x 3.8 dS/m), where 1.88 is the appropriate concentration factor selected from Table 30. If the crop to be grown is cotton with a threshold $EC_e$ tolerance level of 8 dS/m (see Table 13), the salinity level is judged acceptable for surface irrigation, since the predicted resulting average soil salinity ($EC_e$ basis) is but 7.1 dS/m. In terms of actual soil water salinity at field capacity, the corresponding electrical conductivity would be 14.2 dS/m. The corresponding predictions of salinity made using Watsuit were 6.35 ($EC_e$ basis) and 12.7 ($EC_{sw}$ basis). The conservative results obtained with the non-computer method which ignore salt precipitation are sufficiently close to the Watsuit results to justify their use for practical assessment purposes.

The permeability hazard is assessed by ascertaining whether the adj. $SAR_{iw}$ - $EC_{iw}$ combination lies to the left (problem likely) or right (no problem likely) of the threshold relation for the soil (or Figure 2). To illustrate, the point corresponding to the SAR and EC of the Pecos well water described earlier plotted on Figure 2 falls well within the unlikely problem area. Hence, no permeability and crusting problems are expected from the use of

**FIGURE 12**
**Relationship between permissible average concentration factor for the rootzone ($F_c'$) and the leaching requirement ($L_r$)**




this water for irrigation. The corresponding prediction of surface soil $SAR_{sw}$ made using Watsuit was 6.4. The result obtained with the non-computer method is sufficiently close to 6.4 to justify its use for practical assessment purposes. There is no need to adjust the $SAR_{iw}$ for losses (or gains) in calcium in this case. Significant Ca loss will not occur with this gypsiferous (not alkaline) water because there is nothing to cause gypsum precipitation at the soil surface (where $F_c = 1$). The equilibrium SAR in the topsoil due to gypsum incorporation could be predicted, if desired, using Table 31 and Figure 11 and the procedures described in the preceding section.

Calcium deficiencies and chloride toxicities are assessed analogously to that described earlier for Watsuit, except chloride concentration is calculated as ($Cl_{iw} \cdot F_c$), where values of Fc are obtained from Table 30, and $Ca_e$ concentration is calculated as described in the preceding section.

The leaching fraction required at steady-state to prevent the excessive accumulation of salts (or of a specific solute) in soils, is referred to as the leaching requirement ($L_r$). $L_r$ for salinity may be derived directly from Figures 8 and 9 (or for chloride and boron using analogous relationships prepared from the data of Table 30). The intersection of the maximum tolerable level of salinity for a given crop with the curves shown in the figures gives the minimum LF required (thus $L_r$) to keep salinity below the crop tolerance threshold for a given $EC_{iw}$. The most limiting $L_r$ of the three (EC, B, or Cl) is the one that must be selected for management needs. Alternatively, leaching requirement may be estimated using the relationships given in Figure 12 (after Rhoades and Loveday 1990) and the maximum allowable $F_c$ value which is calculated as the ratio: maximum permissible level(s) of salinity (or chloride or boron) in the soil/salinity level of the irrigation water.

Complete uniformity of leaching is assumed in the above assessment of leaching requirement. In actuality, such uniformity is seldom attained in field practice and specific allowance should be made for each factor that causes less than perfect efficiency. Most crops require very little leaching ($L_r < 0.15$) when they are irrigated with typical surface waters and the LF values being attained in most irrigation projects could and should be reduced (van Schilfgaarde *et al.* 1974).

The above procedures for assessing water suitability for irrigation and for determining $L_r$ are simple and the logical consequence of the following assumptions: (i) steady-state, (ii) mass conservation of salt in the non-computer approach, (iii) a 40:30:20:10 water uptake pattern within the rootzone, (iv) crop response to average rootzone salinity with conventional irrigation and water-uptake-weighted rootzone salinity with drip irrigation, and (v) uniformity of infiltration. The $L_r$ values obtained with this method agree closely with those calculated by the empirical method (Rhoades 1974), are much lower for crops of high salt tolerance than those calculated by the method of Handbook 60 (US Salinity Laboratory 1954) but similar for crops of low salt tolerance, and support the reduced leaching requirement of most crops as concluded by van Schilfgaarde *et al.* (1974).

## Use of a Production-Function Model

### *Description of input requirements and operation*

In Watsuit, the effect of salinity on evapotranspiration (ET) is not taken into account in a direct way. Rather, it is assumed that there will be no loss in yield, hence in ET, so long as the threshold level of ECe, $EC_{\acute{e}}$, is not exceeded. The suitability of the water for irrigation is judged simply by ascertaining whether or not the predicted level of soil salinity resulting from irrigation will exceed ECe. Thus, knowledge of ET is not needed to use Watsuit. However, if it is desirable to calculate actual irrigation water requirements and resulting drainage volumes and soil salinity under less than optimum yield conditions, some approach which accounts for salinity effects on ET is needed. The techniques of Letey *et al.* (1985; 1990), Letey and Dinar (1986), Solomon (1985) and Dinar *et al.* (1986) can be used for this purpose; all are similar in principle.

Solomon (1985) presented the general theory of the technique and Letey *et al.* (1985) developed a practical version (model). A modified version of the latter model is used herein. The basic premise of the approach is that a unique relationship exists between yield and ET for a given crop and climate which is independent of whether the water stress leading to the reduced ET is caused by deficit water supply, excess salinity, or some combination of the two. The following thought of Solomon (1985) expresses this premise: "Irrigating with saline water will cause some degree of salinization of the soil. This, in turn, will cause a decrease in crop yield relative to yield under nonsaline conditions. This reduced yield ought to be associated with a decrease in plant size and a decrease in seasonal ET. But as ET goes down, effective leaching will increase mitigating the initial effect of the saline irrigation water. For any given amount and salinity of irrigation water, there will be some point at which values for yield, ET, leaching, and soil salinity all are consistent with one another. The yield at this point is the yield to be associated with a given irrigation water quantity and salinity".

Letey *et al.* (1985) combined three relationships: yield and ET, yield and average rootzone salinity, and average rootzone salinity and leaching fraction to develop an equation which relates yield to the amount of seasonal applied water of a given salinity for steady-state conditions. A linear relationship between yield and ET is used in the model. The piecewise linear relationship proposed by Maas and Hoffman (1977) is used to relate yield and average rootzone salinity. The exponential water uptake function of Hoffman and van Genuchten (1983) is used to relate average rootzone salinity and leaching fraction (which is based on steady-state assumptions). Combination of these three relationships provides a model for predicting salinity, yield, drainage volume, and EC of the water percolating below the rootzone for given quantities of seasonal applied water (AW) of given salinities for steady-state conditions. The mathematical expressions comprising the model are given elsewhere (Letey *et al.* 1985). AW includes both rainfall and irrigation, but does not include runoff. The model assumes uniform water application and does not adjust for salt precipitation or dissolution; nor does it account for matric stresses, use or storage of soil water, or effects of irrigation frequency, water table and water composition.

The advantage of this model is that only relatively simple calculations and measurements, are used to predict crop yield losses, drainage volume and resultant soil salinity. Thus, with use of this model one can judge the suitability of the water for irrigation in terms of the absolute amount of water to be applied and expected rainfall. However, one needs to know the crop production - function (yield versus applied water relation) for the crop in the absence of salt stress. This function can be predicted using the methods of Doorenbos and Kassam (FAO 1979) or obtained from data given in Stewart and Nielsen (1990).

The model of Letey *et al.* (1985) has been modified to give results in terms of relative yield and relative applied water (in terms of $ET_{max}$, i.e. non-stressed ET for the crop and climate). A floppy disk of the model will be provided on request from FAO or from the senior author. The results apply to the whole crop season. Volume weighted average water salinity is used to adjust for rainfall. Table 32 shows the monitor display during data entry. The variable inputs include the threshold salinity and % slope reduction values (according to Eq. 1) for the crop in question (obtain from Tables 12 and 13), the minimum amount of water required to produce yield for the crop (see FAO 1979 or Stewart and Nielsen 1990), the number of irrigation waters to be inputted, and the EC of these irrigation waters. The values of the fixed, or calculated, inputs are also given in Table 32. In this case, the value for the amount of applied water when yield is zero is 25 and, thus, the resulting value of the production function slope is 1.33. The lowest quantity of applied water is 60 and it is incremented in amounts of 10 up to 140.

### *Example of use to assess water suitability for irrigation*

For purposes of illustration, the specific conditions of this example are as follows. Wheat is to be grown with Pecos River water ($EC_e$ = 3.8 dS/m) in a region of no rainfall. The threshold salinity for wheat is 6.0 dS/m and the slope of its yield-salinity curve is 7.1% (obtained from Table 13). The minimum amount of water (expressed as a percentage of $ET_{max}$) required to produce wheat under non-saline conditions is 25 (obtained from page 411

TABLE 32

**Terminal display of input requirement of the water production function model and predictions for example case of Pecos river water**

```
*****************************************************************
        Water Production Function Model for Saline Irrigation Water
*****************************************************************

Fixed Input:

  Max ET                                          =   100.00
  Max Yield                                       =   100.00
  Production Function Slope (S)                   =     1.33
  Applied Water When Yield = Ymax                 =   100.00
  Initial Value for Numerics                      =    10.00
  Upper Limit of Iterations                       =     1990
  Lowest Quantity of Applied Water                =       60
  High Quantity of Applied Water                  =      140
  Increment of Water Quantities                   =       10
  Numeric Tolerance                               =    .0001

Variable Input:

  Threshold Salinity (EC dS/m)                    =      6.0
  Slope of Yield Salinity Curve (%)               =     7.10
  Applied Water When Yield = 0                    =    25.00
  EC of Irrigation Water (dS/m)                   =      3.8
```

Output

| AW | DP | LF | $EC_i$ | $EC_d$ | $RY_{ns}$ | YD | $RY_s$ |
|---|---|---|---|---|---|---|---|
| 60 | 7.500 | 0.125 | 3.800 | 30.398 | 46.667 | 10.001 | 36.666 |
| 70 | 9.031 | 0.129 | 3.800 | 29.455 | 60.000 | 12.041 | 47.959 |
| 80 | 10.542 | 0.132 | 3.800 | 28.837 | 763.333 | 14.056 | 59.278 |
| 90 | 12.042 | 0.134 | 3.800 | 28.402 | 86.667 | 16.055 | 70.611 |
| 100 | 13.534 | 0.135 | 3.800 | 28.077 | 100.000 | 18.045 | 81.955 |
| 110 | 17.967 | 0.163 | 3.800 | 23.266 | 100.000 | 10.622 | 89.378 |
| 120 | 23.331 | 0.194 | 3.800 | 19.545 | 100.000 | 4.441 | 95.559 |
| 130 | 30.000 | 0.227 | 3.800 | 16.710 | 100.000 | 0.000 | 100.000 |
| 140 | 40.000 | 0.261 | 3.800 | 14.558 | 100.000 | 0.000 | 100.000 |

of Stewart and Nielsen 1990). The data in Table 32 show the output and illustrate use of the water production model to predict the relative yield decrement from salinity (YD), the relative amount of deep percolation (DP), the leaching fraction (LF), the relative yield of the crop when irrigated with non-saline water applied (AW) in various amounts (% units) relative to ET ($RY_{ns}$), the relative yield when irrigated with the saline water of EC, ($RY_s$), and the EC of the drainage water ($EC_d$). The relative yield losses due to deficit irrigation *per se* ($RY_{ns}$) occur with each application of water less than 100 (equivalent to $ET_{max}$ without salinity stress) as shown in Table 32. With $EC_a$ of 3.8 dS/m, additional yield losses occur (YD) resulting in the $RY_s$ values shown. From these values it is evident that full yield ($RY_s$ = 100) requires the use of 110 units of applied water. The resulting drainage is equivalent to a leaching fraction of 0.084. The drainage water will be very saline ($EC_a$ = 45 dS/m). Based on these results it can be concluded that Pecos River water can be used to grow wheat without yield loss at practical levels of water application and leaching.

# Chapter 5

# Environmental and ecological aspects

## NATURE AND CAUSES OF ENVIRONMENTAL PROBLEMS

The world's natural resource base for food production has already been weakened and the likely additional strain of the expected increase in population and agricultural activity needed to feed it are posing a threat to the prospects of sustainable development in many countries (UN 1990). It is pertinent at this stage to define sustainable agricultural development: "Sustainable agriculture is the management and conservation of the natural resource base, and the orientation of technological and institutional change in such a manner as to ensure the attainment and continued satisfaction of human needs for present and future generations. Such sustainable development in the agriculture, forestry and fisheries sectors conserves land, water, plant and animal genetic resources, is environmentally non-degrading, technically appropriate, economically viable and socially acceptable" (FAO 1989). Environmental stress is often the result of the excessive demand for scarce natural resources and the related pollution of the land and water generated by over-development and by poverty. The latter occurs when the poor degrade and destroy their immediate environment as they over-use marginal lands for agriculture and dispose of wastes without treatment to common water supplies in order to meet their living needs. Hence an objective of soil and water conservation must also be to create an economic base which makes it more profitable to conserve and protect resources than to destroy them.

There are a number of potentially undesirable impacts on the environment, as well as on the economic and social components of society, caused by improper irrigation which must be considered if agricultural production is to be sustained, even more so if it is to be expanded by the use of saline waters. These impacts can potentially have far-reaching consequences on present as well as future generations and, hence, can affect the very sustainability of irrigated agriculture. In this chapter, some of the concerns about the environment (within and beyond the farm boundaries), the ecology and the long-term viability of irrigation are discussed.

Figure 13 represents a typical irrigation project and its surrounding area and can be used to help portray the various environmental and ecological problems associated with irrigation (Kandiah 1990). Water is diverted from the source and transported through a system of canals to irrigate the cropland. Part of the resulting drainage water is collected and discharged into a nearby stream by means of a system of collector and disposal drains. In this particular project, the irrigation water is low in salinity, crop yields are good and the farmers are profiting. No immediate threat of salinization or waterlogging is evident within the project itself. However, as a result of project activities:

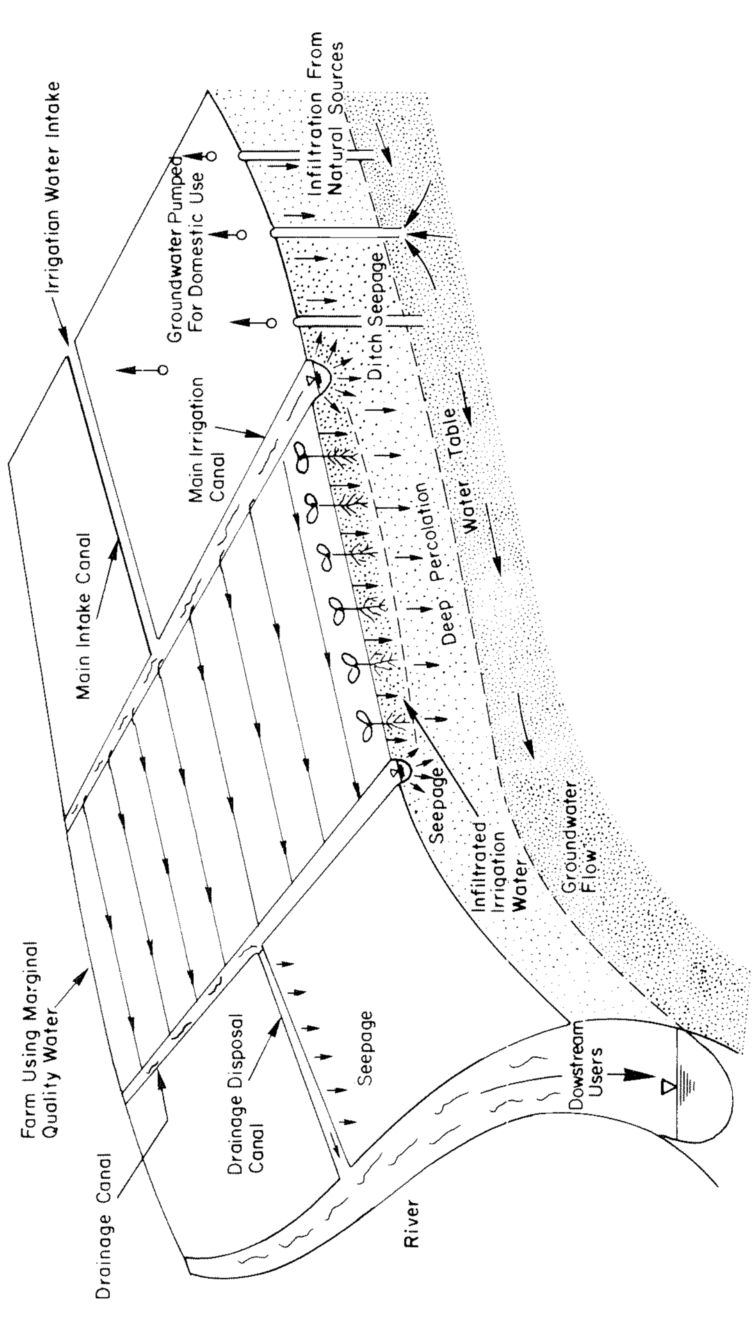



FIGURE 13
Schematic representation of a typical irrigation system and its environment (Kandiah 1990)

- the area immediately below the project, which is a nature reserve, has become waterlogged and salinized due to the build-up of a shallow water table there caused by excessive on-farm deep-percolation and seepage of drainage water from the collector and disposal drains within the project;

- the stream into which the drainage from the project is discharged has become polluted with salts and agrochemicals to the point that is no longer suitable for drinking and other domestic purposes by a community in the downstream area;

- the groundwater beneath the project has also become polluted because the subsurface drains do not fully intercept the downward flow of percolated water from the irrigated land. This drainage water is high in salts, nitrates, selenium, boron, pesticides and some other agrochemicals and is a potential health hazard to the people who are using the groundwater for domestic purposes;

- the natural vegetation of the reserve land has undergone undesirable changes in its extent and composition caused by waterlogging and salinization of the area and, as a consequence, the wildlife population has been diminished and altered in its makeup;

- the water birds which were attracted to the wetland habitat are dying due to selenium toxicity;

- fishermen and hunters who have consumed the fish and game of this wetland and preserve are suffering chronic health problems due to excessive consumption of high selenium (and other trace elements);

- the drainage canals and associated wetlands have become breeding sites for mosquitoes; as a result malaria outbreaks are occurring in the project area.

This hypothetical example, albeit an exaggerated one, illustrates the multitude of potential environmental, ecological, health and social problems that can and do sometimes arise as a result of improperly planned and managed irrigation and drainage systems. The use of saline waters for irrigation can either accentuate or help mitigate these problems. Most of the problems depicted in this hypothetical situation can be prevented or greatly minimized with proper design and operation of the irrigation and drainage systems. Implementing an appropriate means of disposing of the saline drainage effluent resulting from irrigation is very important in this regard.

There are at least four major environmentally-related potential hazards associated with irrigation in general and with the use of more saline waters in particular. They are: **loss in soil productivity** due to salinity and waterlogging, **pollution of associated water resources** with salts and toxicants by drainage, **damage to the associated ecosystems** and **increased risk to public health** resulting from water pollution and waterlogging.

## Soil Degradation (Salinization and Waterlogging)

Large and increasing proportions of the world's irrigated land are deleteriously affected by waterlogging and excessive salinity. While the exact area affected is not known, it is estimated that approximately 25 percent of the world's irrigated land is damaged by salinization (Postel 1989; see Table 33). Some claim that up to 50 percent of the world's

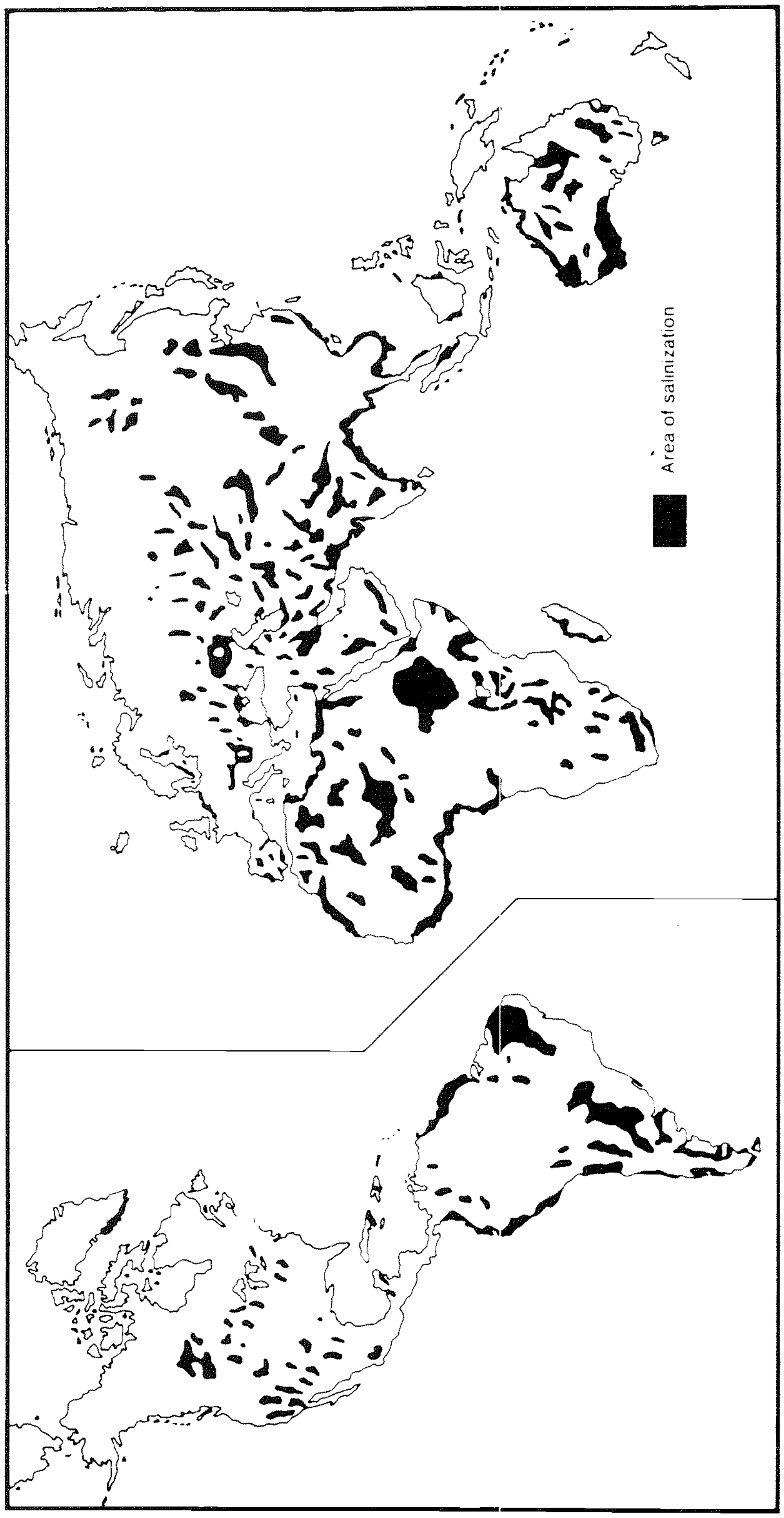



FIGURE 14
Global distribution of salt-affected soils (after Szabolcs 1985)

TABLE 33
**Irrigated land damaged by salinization, top five irrigators and world estimate, mid-1980s** (after Postel 1989)

| Country | Area damaged (million hectares) | Share of irrigated land damaged (%) |
|---|---|---|
| India | 20.0 | 36 |
| China | 7.0 | 15 |
| United States | 5.2 | 27 |
| Pakistan | 3.2 | 20 |
| ex-Soviet Union | 2.5 | 12 |
| Total | 37.9 | 24 |
| WORLD | 60.2 | 24 |

irrigated land may be affected by salt (Adams and Hughes 1990). Certainly no continent is free from salt-affected soils (see Figure 14). Serious salt-related problems occur within the boundaries of at least seventy-five countries (Rhoades 1988b). Countries with notable salinity problems include Australia, China, Egypt, India, Iraq, Mexico, Pakistan, the republics of the ex-Soviet Union, Syria, Turkey, and USA.

A close relationship exists between the depth and salinity of the shallow groundwaters, the soil hydraulic properties and the extent of salt accumulation in soils, especially in natural, semi-arid regions. The major saline regions of the world are generally found in semi-arid and arid and relatively low-lying, poorly drained lands. This is the result of the mobilization of large quantities of salts by excessive irrigation and leaching and the subsequent accumulation of the salt in localized areas with restricted drainage. Such areas are often found in lower-lying regions of the landscape where the water table is at or near the soil surface, and where the salts have ascended into the soil due to evaporation-driven processes. Restricted drainage may be due to low permeability of the fine-textured soils or to the presence of a shallow groundwater. Shallow groundwaters are often related to topographic position. The drainage of waters from the higher-elevation regions of valleys and basins may raise the water table in the lower-lying lands so that it is close (within 2 m) to the soil surface. Permeability of the soils is typically lower in these basin positions because of the higher content of alluvial clays generally found in basin soils, which impedes the downward movement of water and results in poor drainage. Many irrigation projects are located in these lower lying alluvial- and basin-position areas because of their favourable slopes (more level conditions) and closer proximities to easily accessible water supplies.

While salt-affected soils occur extensively under natural conditions, the salt problems of greatest importance to agriculture arise when previously productive cultivated soil becomes salinized as a result of irrigation (so-called secondary salinization). Human activities have modified (likely have increased) the extent of salt-affected areas considerably by the redistribution of water (hence salt) through irrigation. The development of large-scale irrigation projects, which involves diversions of rivers, construction of large reservoirs and the irrigation of large landscapes, causes large changes in the natural water and salt balances of entire hydrogeologic systems. The impact of irrigation often extends well beyond that of the immediate irrigated area; even neighbouring nations can be affected. Water infiltrated into the soil in excess of that used by the agricultural crops passes beyond the rootzone. This water often dissolves salts of geologic origin from the soils and underlying substrata and causes waterlogging in lower areas where it accumulates. When this occurs, soluble salts present in the ground are mobilized and transported to the lower areas where they accumulate and over time salinize the groundwaters and the soils in the areas where the water tables approach ground level.

The problems of waterlogging and secondary salinity prevalent in most irrigated lands have resulted from the excessive use of water for irrigation (resulting from inefficient irrigation systems, poor distribution systems and poor on-farm management practices), from inadequate and inappropriate drainage management, and from the discharge of "spent" drainage water into good-quality water supplies which are used elsewhere for crop production. It is not unusual to find that less than 60 percent of the water diverted for irrigation is used in crop transpiration (Jensen *et al.* 1990; Biswas 1990). It is important to note that these problems have occurred even where low-salinity waters have been used for irrigation. Thus it might be argued that the use of saline waters for irrigation can only increase these problems, since more salt will be added to the soils with such waters and relatively more leaching (hence drainage) is required in this case for salinity control of the rootzone. However, paradoxically, such need not be the case.

It should also be understood that some soil and water salination is inevitable with irrigation. Typical irrigation waters may contain from 0.1 to 4 kg of salts per $m^3$ and are generally applied at annual rates of 1.0 to 1.5 m. Thus, from 1 to 60 metric tonnes of salt per hectare may be added to irrigated soils annually. As discussed earlier, the salt contained in the irrigation water is left in the soil as the pure water passes back to the atmosphere through the processes of evaporation and plant transpiration. Therefore, water in excess of evapotranspiration must be applied with irrigation to achieve leaching and to prevent excess salt accumulation in the rootzone. This water must drain from the rootzone. Seepage from delivery canals occurs in many irrigation projects. These drainage and seepage waters typically percolate through the underlying strata (often dissolving additional salts in the process), flow to lower elevation lands or waters and frequently cause problems of waterlogging and salt-loading there. Saline soils are formed in such areas through the processes of evaporation. Ground- and surface-waters receiving these drainage and seepage waters typically are increased in salt concentration. Thus the problems of waterlogging and secondary salinization are related to inefficient irrigation and/or inadequate drainage.

The primary sources of drainage from an irrigation project are bypass water, canal seepage, deep percolation and surface (tailwater) runoff. Bypass water is often required to maintain hydraulic head and adequate flow through gravity-controlled canal systems. It is usually returned directly to the surface water supply and few pollutants, if any, are picked up in this route. Evaporation losses from canals commonly amount to only a small percentage of the diverted water. However, seepage from unlined canals is often substantial. Such seepage typically contributes significantly to high water tables, increases groundwater salinity and phreatophyte growth, and generally increases the amount of the required drainage (and its salinity) from irrigated areas. Biswas (1990) estimated that 57 percent of the total water diverted for irrigation in the world is lost from conveyance and distribution canals. If the water passes through salt-laden substrata or displaces saline groundwater, the salt pickup from these sources can be substantial.

From the above it is concluded that the majority of the soil degradation (salinity and waterlogging) problems related to irrigated agriculture occurring throughout the world are caused by inefficiencies in the distribution and application of irrigation water, the resulting mobilization and accumulation of excess water and salts in local regions related to hydrogeologic conditions and the return of saline drainage waters to fresh water supplies. The use of saline waters of the levels advocated herein should not result in excessively saline soils nor cause waterlogging with proper management. In fact, the interception of drainage waters percolating below rootzones and their reuse for irrigation should reduce the soil degradational processes associated with excessive deep percolation, salt mobilization, waterlogging and secondary salinization that typically operate in irrigated lands. It should also reduce the water pollution problems associated with drainage discharge to good-quality water supplies. An integrated irrigation and drainage management system for facilitating the use of saline drainage waters for irrigation, while minimizing the soil degradational and water pollution problems associated with drainage, is presented in Chapter 6.

## Water pollution

The role of irrigated agriculture in soil salinization has been well recognized for hundreds of years. However, it is of relatively recent recognition that salinization of water resources from agricultural activities is a major and widespread phenomenon of possibly even greater concern to the sustainability of irrigation than is that of the salinization of soils, *per se*. Indeed, only in the past few years has it become apparent that trace toxic constituents, such as Se, Mo and As, in agricultural drainage waters may cause pollutional problems that threaten the continuation of irrigation in some projects.

As explained above, water infiltrated into the soil in excess of that used by the agricultural crops passes beyond the rootzone. This water, together with that deep percolating from canal seepage, often dissolves additional salts (over and above those present in the irrigation water) from the soils and underlying substrata. Such mobilized salts, when transported to receiving waters, are a source of pollution, as are the salts applied in the irrigation water which have become concentrated in the drainage water through evapotranspiration. These saline drainage waters pollute good-quality receiving waters when they are allowed to mingle with them. Addition potential sources of pollutants from irrigation are the agrochemicals (fertilizers and pesticides) applied to the soils which may also be, in part, mobilized (by leaching) and discharged in the drainage water.

Representative compositions of drainage waters leaving cropped rootzones at steady-state in a controlled lysimeter experiment when irrigated with a range of irrigation waters (see Table 34) are shown in Table 35 for three different leaching fractions. The salt loads of these irrigation ($V_{iw}C_{iw}$) and drainage ($V_{dw}C_{dw}$) waters and their differences ($V_{dw}C_{dw} - V_{iw}C_{iw}$) are shown in Table 36. Note that the total salt-load discharged from the irrigated rootzone was reduced by about 2 to 12 metric tons/ha/year as the leaching fraction was reduced from 0.3 to 0.1.

The reduction in salt return shown in Table 36 is achieved in three ways. Less salt is discharged with reduced leaching because less irrigation water, and hence salt, is applied. The percent reduction in salt discharge due to reduced application is 100 $(V_H - V_L)/V_L$, where $V_H$ and $V_L$ are volumes of irrigation water applied with high and low leaching, respectively. Reduced leaching reduces salt discharge still further because the fraction of applied salt that precipitates in the soil increases. A further benefit of reduced leaching is that fewer additional salts are picked up from the weathering and dissolution of soil minerals, because the through-put of drainage water is reduced and the "solvent" capacity of the more saline water is likewise reduced. The latter two benefits are demonstrated in Table 37 where the net effects of soil minerals weathering and dissolution ($S_m$) and salt precipitation ($S_p$), as determined in the lysimeter experiment, are given in terms of percentage of the salt load of the irrigation waters ($V_{iw}C_{iw}$). These data show that weathering and dissolution are less and salt precipitation is greater as the leaching fraction decreases. They also serve to illustrate the following important points. As compared to high leaching, minimized leaching increases the concentration of the drainage water; it reduces the amount of salt added to the soil and

TABLE 34
**Compositions of river waters used for irrigation** (after Rhoades *et al.* 1974)

| | Water No. (River) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| | Feather at Nicolaus, California | Grand near Wakpala, S. Dakota | Missouri at Nebraska City, Nebraska | Salt below Stewart Mtn., Arizona | Colorado near Mexican Border | Sevier, near Lynndyl, Utah | Gila, below Gillespie Dam, Arizona | Pecos near Artesia, New Mexico |
| EC* dS/m | 0.10 | 0.94 | 0.91 | 1.56 | 1.27 | 2.03 | 3.14 | 3.26 |
| $Ca^{++}$ $mmol_c/l$ | 0.45 | 2.00 | 4.06 | 3.15 | 6.95 | 3.71 | 7.22 | 16.98 |
| $Mg^{++}$ $mmol_c/l$ | 0.36 | 0.79 | 1.92 | 1.35 | 3.63 | 6.05 | 5.88 | 9.07 |
| $Na^{+}$ mmolc/l | 0.20 | 7.08 | 3.02 | 9.62 | 3.35 | 10.62 | 18.55 | 11.38 |
| $K^{+}$ $mmol_c/l$ | 0.04 | 0.19 | 0.10 | 0.17 | 0.22 | 0.15 | 0.09 | 0.08 |
| Sum of cations $mmol_c/l$ | 1.05 | 10.06 | 9.10 | 14.29 | 14.15 | 20.53 | 31.74 | 37.51 |
| $HCO_3^-$ $mmol_c/l$ | 0.86 | 6.29 | 3.24 | 3.21 | 3.73 | 5.21 | 3.17 | 3.11 |
| $Cl^-$ $mmol_c/l$ | 0.08 | 0.19 | 1.78 | 10.12 | 1.03 | 9.31 | 20.17 | 12.13 |
| $SO_4^{--}$ $mmol_c/l$ | 0.16 | 3.43 | 4.05 | 0.89 | 9.31 | 5.96 | 8.48 | 22.39 |
| SAR** | 0.30 | 6.00 | 1.80 | 6.40 | 1.50 | 4.80 | 7.30 | 3.20 |

* EC = Electrical conductivity (dS/m)

** SAR = $Na^{+}/[(Ca^{++} + Mg^{++})/2]^{1/2}$, where all concentrations are expressed in $mmol_c/l$.

TABLE 35

**Compositions of drainage waters from irrigated alfalfa rootzone at steady-state** (after Rhoades *et al.* 1974)

| River | LF* | EC** dS/m | Concentration in $mmol_c/l$ | | | | | | | | | SAR*** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Ca | Mg | Na | K | Sum of cations | $HCO_3$ | Cl | $SO_4$ | Sum of anions | |
| Feather | 0.1 | 1.84 | 13.05 | 5.64 | 3.80 | 0.57 | 23.06 | 22.86 | 0.02 | 0.24 | 23.12 | 1.2 |
| | 0.2 | 1.45 | 9.94 | 4.81 | 1.70 | 0.62 | 17.86 | 17.14 | 0.09 | 0.24 | 17.47 | 0.6 |
| | 0.3 | 1.17 | 8.52 | 3.71 | 1.24 | 0.35 | 13.82 | 13.29 | 0.21 | 0.28 | 13.78 | 0.5 |
| Grand | 0.1 | 6.15 | 14.40 | 7.18 | 57.66 | 0.94 | 80.18 | 39.16 | 0.34 | 39.30 | 98.80 | 17.6 |
| | 0.2 | 3.51 | 7.69 | 1.46 | 33.25 | 0.36 | 42.76 | 26.83 | 0.14 | 15.26 | 42.23 | 15.5 |
| | 0.3 | 2.75 | 6.55 | 2.60 | 23.98 | 0.28 | 33.41 | 21.76 | 0.15 | 10.62 | 32.47 | 11.2 |
| Missouri | 0.1 | 5.66 | 32.21 | 13.28 | 28.45 | 2.80 | 74.74 | 26.69 | 12.98 | 34.45 | 74.12 | 6.0 |
| | 0.2 | 3.12 | 18.08 | 5.92 | 14.22 | 0.30 | 38.52 | 17.68 | 5.34 | 14.84 | 37.86 | 4.1 |
| | 0.3 | 2.65 | 14.79 | 6.55 | 10.61 | 0.32 | 32.27 | 15.22 | 4.62 | 12.02 | 31.86 | 3.2 |
| Salt | 0.1 | 11.59 | 25.96 | 9.66 | 87.19 | 0.76 | 123.47 | 23.02 | 91.19 | 9.67 | 123.88 | 20.7 |
| | 0.2 | 6.42 | 15.84 | 6.31 | 44.38 | 0.75 | 67.28 | 20.22 | 43.00 | 3.51 | 66.73 | 13.3 |
| | 0.3 | 4.52 | 12.49 | 5.92 | 29.12 | 0.48 | 48.01 | 15.15 | 28.35 | 2.60 | 46.10 | 9.6 |
| Colorado | 0.1 | 7.27 | 42.46 | 28.00 | 34.69 | 1.17 | 106.32 | 25.16 | 14.16 | 68.60 | 107.92 | 5.8 |
| | 0.2 | 4.56 | 31.42 | 15.91 | 19.17 | 0.36 | 66.86 | 18.28 | 4.77 | 43.04 | 66.09 | 3.9 |
| | 0.3 | 3.59 | 27.02 | 10.39 | 10.66 | 0.31 | 48.38 | 16.88 | 3.66 | 28.36 | 48.90 | 2.5 |
| Sevier | 0.1 | 12.18 | 38.13 | 25.64 | 79.30 | 2.08 | 145.15 | 21.42 | 75.73 | 48.63 | 145.78 | 14.0 |
| | 0.2 | 7.45 | 22.45 | 16.83 | 46.17 | 0.77 | 86.25 | 19.89 | 39.81 | 25.96 | 85.66 | 10.4 |
| | 0.3 | 5.69 | 16.56 | 15.32 | 33.06 | 0.33 | 65.27 | 18.69 | 28.30 | 17.97 | 64.96 | 8.3 |
| Gila | 0.1 | 20.59 | 59.55 | 36.48 | 151.90 | 1.40 | 249.33 | 20.62 | 163.80 | 65.40 | 249.82 | 21.9 |
| | 0.2 | 12.23 | 34.81 | 20.90 | 84.61 | 0.58 | 140.90 | 20.62 | 83.93 | 37.04 | 141.59 | 16.0 |
| | 0.3 | 10.59 | 31.35 | 19.13 | 70.42 | 0.71 | 121.61 | 17.32 | 71.48 | 31.25 | 120.05 | 14.0 |
| Pecos | 0.1 | 17.72 | 53.84 | 75.92 | 106.80 | 0.88 | 237.44 | 22.32 | 120.40 | 94.86 | 237.58 | 13.3 |
| | 0.2 | 9.63 | 39.44 | 37.47 | 47.29 | 0.77 | 124.97 | 13.21 | 48.61 | 62.01 | 223.83 | 7.6 |
| | 0.3 | 8.30 | 42.50 | 30.47 | 36.41 | 0.40 | 109.78 | 12.35 | 37.62 | 59.51 | 109.48 | 6.0 |

* LF = leaching fraction ** EC = electrical conductivity dS/m

*** SAR = $Na^+/[(Ca^{++} + Mg^{++})/2]^{1/2}$, where all concentrations are expressed in $mmol_c/l$.

TABLE 36
**Salt burdens of applied waters ($V_{iw}C_{iw}$) and drainage waters ($V_{dw}C_{dw}$), differences (SB) and potential for reducing salt return, metric tons/ha/year** (after Rhoades and Suarez 1977)

| River | Salinity* | Fraction reduction in salt | | | | | | | | | Return** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | LF = 0.1 | | | LF = 0.2 | | | LF = 0.3 | | | |
| | | $V_{iw}C_{iw}$ | $V_{dw}C_{dw}$ | SB | $V_{iw}C_{iw}$ | $V_{dw}C_{dw}$ | SB | $V_{iw}C_{iw}$ | $V_{dw}C_{dw}$ | SB | |
| Feather | 1.0 | 0.67 | 1.28 | +0.60 | 0.76 | 2.33 | +1.57 | 0.87 | 3.36 | +2.49 | 2.08 |
| Grand | 10.1 | 6.12 | 4.46 | -1.66 | 6.90 | 6.14 | -0.76 | 7.88 | 8.29 | +0.40 | 3.83 |
| Missouri | 9.1 | 5.89 | 5.42 | -0.47 | 6.63 | 6.83 | +0.20 | 7.59 | 8.36 | +0.76 | 2.93 |
| Salt | 14.3 | 10.15 | 9.23 | -0.92 | 11.42 | 11.76 | +0.34 | 13.06 | 14.76 | +1.70 | 5.53 |
| Colorado | 14.1 | 8.29 | 6.23 | -2.08 | 9.32 | 8.94 | -0.38 | 10.66 | 10.55 | -0.11 | 4.32 |
| Sevier | 20.5 | 13.19 | 10.82 | -2.37 | 14.87 | 14.27 | -0.60 | 17.00 | 17.67 | +0.67 | 6.85 |
| Gila | 31.7 | 20.36 | 18.73 | -1.64 | 22.94 | 23.39 | +0.45 | 26.23 | 27.80 | +1.57 | 9.07 |
| Pecos | 37.5 | 21.19 | 12.92 | -8.27 | 23.86 | 18.12 | -5.73 | 27.28 | 24.82 | -2.46 | 11.89 |

* Total concentration ($mmol_c/l$).
** The difference in salt output in drainage water between that achieved with leaching fractions of 0.3 and 0.1 assuming a consumptive use requirement of 91 cm/year.

discharged from irrigated rootzones because it maximizes the precipitation of applied Ca, $HCO_3$ and $SO_4$ salts as carbonates and gypsum minerals in the soil, and it minimizes the "pick-up" of weathered and dissolved salts from the soil.

TABLE 37
**Net effect of LF on ($S_m$-$S_p$) for six representative river types expressed as percentage of salt input** (from Rhoades *et al.* 1974; on $mmol_c/l$ basis)

| River | 100 ($S_m$-$S_p$)/$V_{iw}C_{iw}$ | | |
|---|---|---|---|
| | 0.1 LF | 0.2 LF | 0.3 LF |
| Feather | +180 | +271 | +348 |
| Missouri | -9 | +5 | +13 |
| Colorado | -24 | -3 | +5 |
| Salt | -10 | +6 | +12 |
| Sevier | -25 | -8 | -3 |
| Pecos | -33 | -21 | -10 |

The experimental data of Tables 35 to 37 agree with those calculated using Watsuit (Oster and Rhoades 1975; 1990; Rhoades and Merrill 1976). Thus, it is concluded that salt precipitation and dissolution reactions of such minerals can be modelled and the compositions of a soil and drainage water can be adequately predicted for different irrigation waters and leaching fractions using this model. An example of the use of Watsuit for such purposes was given earlier (Tables 26 and 27).

TABLE 38
**Predicted effect of reduced leaching fraction on salt and water balance of the Wellton-Mohawk project**[1]
(after Rhoades and Suarez 1977)

| Item | Unit | High LF (0.42) | Low LF (0.10) |
|---|---|---|---|
| ($S_m$-$S_p$)[2] | % | +8 | -25 |
| $V_{iw}$ | $m^3$ | 638 x $10^6$ | 411 x $10^6$ |
| $V_{dw}$[3] | $m^3$ | 286 x $10^6$ | 40.7 x $10^6$ |
| Salt load | metric tons | 586 000 | 262 000 |
| Concentration | mg/l | 2170 | 6375 |

1 Colorado River water containing 158 metric tons of salt/100 $m^3$ is applied annually to 26 305 ha to meet the estimated consumptive use of 370 x $10^6$ $m^3$.
2 ($S_m$-$S_p$) is the net effect of mineral weathering or dissolution ($S_m$) and salt precipitation ($S_p$) on the salt load of the drainage water relative to that of the irrigation water ($V_{iw}C_{iw}$).
3 $V_{iw}$ and $V_{dw}$ are volume of infiltrated irrigation and subsurface drainage water, respectively.

The preceding data clearly demon-strate that decreasing the leaching fraction can significantly decrease the volume and the salt load of drainage waters discharged from rootzones. Where the drainage waters can be intercepted before being returned to surface or groundwater bodies, such reductions are of substantial benefit when they are to be treated to prevent water pollution. Illustrative of such a situation is the Wellton-Mohawk Project in Arizona where the drainage water is collected by pumps and conveyed in discharge canals to a plant for desalinization (see Table 38). With reduced leaching, water diversion into the project can be reduced by 227 x 106 $m^3$, salt return can be reduced by 324 000 metric tons, drainage return-flow can be reduced by 227 x 106 $m^3$, and the drainage water can be concentrated to the point that it would have nearly no remaining value for irrigation.

Minimizing leaching may, or may not, reduce salinity degradation of the receiving water where the drainage water is returned to a surface or groundwater. A reduction of degradation will generally always occur where saline groundwaters with concentrations in excess of those of the recharging rootzone drainage waters are displaced into the receiving water or where additional salts, other than those derived from the irrigation water *per se*, are encountered

TABLE 39

**Effect of reduced leaching on river salinity where highly saline groundwater of independent and constant salt composition is displaced into the river with low and high leaching, simulating Grand Valley, Colorado, conditions** (after Rhoades and Suarez 1977)

| Water | Composition of water in $mmol_c/l$ | | | | | | |
|---|---|---|---|---|---|---|---|
| | Ca | Mg | Na | K | Cl | alkalinity | $SO_4$ |
| Colorado River upstream[1] | 2.59 | 0.96 | 2.49 | 0.06 | 1.91 | 2.31 | 1.88 |
| Groundwater[2] | 23.1 | 42.8 | 30.0 | 0.41 | 15.6 | 10.7 | 70.3 |
| Colorado River downstream (low leaching) | 2.63 | 1.05 | 2.55 | 0.06 | 1.94 | 2.33 | 2.03 |
| Colorado River downstream (high leaching) | 2.79 | 1.49 | 2.84 | 0.06 | 2.08 | 2.35 | 2.75 |

1 Upstream of irrigation diversion point.
2 In aquifer hydraulically connected to Colorado River.

and mobilized in the drainage flow-path and brought into solution by weathering and dissolution processes. An example is the Colorado River through Grand Valley, USA. Here, minimizing leaching reduces the salt load in the river downstream of the project by reducing the "pick-up" of geologic salts as the drainage water percolates past the rootzone and displaces highly saline groundwater present in the underlying cobble aquifer into the river, as illustrated in Table 39. The salinity of the Colorado River is increased by 13% (56 mg/l) and its salt load by 541 000 metric tons by irrigation and drainage processes associated with high leaching. For conditions like these, reduced leaching will always reduce the salinity of the river downstream from the project. Similar results will also occur under conditions where the irrigated soils, or underlying substrata, contain gypsum or other forms of mineral salts.

The above example illustrates well that it is the excess diversion of water for irrigation, concentration of part of this water through evapotranspiration, deep percolation of the concentrated drainage water, mobilization of additional "geologic" salts and return of such waters to surface waters that cause the increase in downstream salinity (pollution) that typifies most river systems used for irrigation and drainage in the world.

For situations where no salts of geologic origin exist in the soils or substrata, the composition of the deeply percolating drainage water is little changed from that leaving the rootzone. For such cases, the composition of the mingled drainage plus receiving water may be the same regardless of leaching fraction, depending upon the saturation status of the receiving water with respect to calcium carbonate and gypsum and fate of water "saved" by reduced leaching. Such cases are more rare than the one described above for the Upper Colorado River; however, the Lower Colorado River is such a case where the "saved" water is passed on downstream and dilutes the returned salts to the same degree regardless of leaching.

As with river systems, degradation of groundwaters receiving irrigation drainage may or may not be benefitted by reduced leaching, depending on the hydrogeologic situation. With no sources of recharge other than drainage return flow, the groundwater eventually tends toward the composition of the drainage water, which will be more saline with low leaching. However, reduced leaching slows the arrival time of the leachate. Thus the groundwater salinity will generally be lower for an interim period of time with reduced leaching (Suarez and van Genuchten 1981). Low leaching management can continuously reduce degradation of the groundwater only if other sources of high-quality recharge into the basin exist and if flow out of the basin is high relative to drainage inflow. For more discussion of the effect of drainage management on groundwater pollution see Rhoades and Suarez (1977).

Agricultural drainage is sometimes intentionally returned to common water supplies in order to conserve water and increase water use efficiency. Water quality agencies often deal with agricultural drainage pollution problems by setting allowable concentrations of total salts and specific solutes in the waters that are returned to the water supply system and by blending or diluting the drainage waters with a good-quality water so that the concentration of total salt (or of a specific solute) in the blend does not exceed a value (the so-called safe limit) that is deemed allowable in the water supply. Such practices may be shortsighted, since they do not consider the potential deleterious effect that the discharge of agricultural drainage water to surface and groundwater supplies and such blending - whether it is natural or intentional - can have upon the usability of the total - and the receiving water supplies. The blending process often reduces the maximum practical benefit that can be derived from the total water supply. The return of saline waters to the water supply, even when sufficient dilution occurs to keep the salinity of the mixture within apparently safe limits, reduces the quantity of the total water supply that can be used in consumptive processes which are limited by salt concentration, such as the growth of salt-sensitive crops.

## Ecosystem Disturbances

Few data exist on the degree of degradation of associated ecosystems which can be caused by irrigation, especially with saline waters. This deficiency is due to both the lack of effort that has been made to acquire such information for vast areas of the world and the incomplete understanding of how many of the ecological systems are affected by waterlogging and salinity. The task is made more difficult by the absence of a practical means to monitor changes in large irrigated landscapes systems and associated environments in response to developmental factors.

The hypothetical example used to introduce this chapter illustrated some of the ways irrigation and drainage can effect wildlife habit, biological diversity and in-stream use of surface water systems. A real example may serve even better to demonstrate the profound effects irrigation and drainage, especially the effects of saline drainage water disposal, may have upon ecological systems and, in turn, their impact on entire irrigation projects. An example of such a mutual dilemma is the Westside area of the San Joaquin Valley of California and the Kesterson Wildlife Refuge, as summarized by San Joaquin Valley Drainage Program (1990).

Before development, the native habitat of the San Joaquin Valley (this area is the heart of the 4.7 million acres (1.9 million hectares) of irrigated land in California, USA) was a lush patchwork of aquatic wetland, riparian forest and valley savannah and it teemed with an abundance and diversity of fish and wildlife found nowhere else in the USA. Grizzly bear, elk, antelope, deer, wolves, quail, geese and a multitude of species of migratory birds, especially waterfowl and shorebirds, populated the Valley. The streams and rivers abounded with trout, salmon and steelhead. Now after about one hundred and fifty years of settlement and the development of irrigated agriculture in the Valley, the quantity and quality of the ecology has been markedly altered. Dams now block most of the major streams to anadromous fish. Impoundments and diversions of the streams for irrigation have depleted the streams of most of their flow, while lack of recharge and discharges of drainage waters to them have increased the salt concentrations of the remaining flow. The change in habitat has been immense. The Central Valley of California has lost, mostly to agriculture, over 91 percent of its original 4 million plus acres (1.62 million hectares) of marsh land. The two major inland lakes (Tulare and Buena Vista) which were once the largest freshwater lakes in the western USA are now farmland. In the San Francisco Bay, which was the outlet for the San Joaquin River and most of the Valley's streams, the water surface has been reduced by 41 percent. Riparian wetlands have been reduced statewide to less than 2% of their original area.

As a consequence of these changes in land use, tremendous losses in native habitat have occurred. Fish and wildlife populations are a fraction of what they were originally. Still substantial populations (about 7 - 8 million ducks and geese) winter in the Valley. However, where once they found about 105 300 hectares of marsh, they now find only 2025 hectares. Where once they could land on 243 000 hectares of freshwater lakes, they now find only 2835 hectares of saline evaporation ponds.

These drastic reductions in the area of native habitat have resulted in population declines in a number of species and plants endemic to the Valley. Several Valley species have become extinct and others are listed as endangered by the Federal or State Governments. Even though irrigated agriculture has nearly completely altered the original ecology and diversity of the San Joaquin Valley, a new ecological concern has recently emerged to threaten the very existence of continued irrigation in a substantial fraction of the San Joaquin Valley. Because of the occurrence of waterlogging and a lack of a final outlet for drainage water disposal in much of the San Joaquin Valley, evaporation ponds were created as local outlets for "waste" disposal from irrigation. One such pond (the so-called Kesterson Reservoir) was constructed in 1975 to operate as a storage and flow regulating facility as part of a proposed drainage canal planned to discharge ultimately to the San Francisco Bay and to serve simultaneously as a wildlife refuge. Because of concerns about potential environmental impacts (nitrates and pesticides, primarily) of the disposal of this agricultural drainage on the Bay, construction of the canal ceased in 1978 and the Kesterson Reservoir (486 hectares) became the terminus of the drainage canal serving 3240 hectares of irrigated land and, effectively, an evaporation pond. At Kesterson, contaminants in the drainage water, specifically selenium at about 35 parts per billion, built up in the food chain, accumulated in the fish and birds using the "pond" and manifested itself by 1982 in gross deformities, reproduction failures and deaths of waterfowl. As a result, in 1985 the Kesterson Reservoir was closed to drainage and the drainage outlets from the source, the Westland Irrigation District, were sealed. Some 2800 hectares of additional evaporation ponds exist in the Valley and another 11 300 hectares are under consideration. However, because of the concerns about the effects of these ponds on the waterfowl, their future is in doubt.

Based on levels of selenium found in a survey of fish and wildlife in the regions of the ponds, health warnings have been issued to avoid or restrict consumption of wild plants, fish and/or wildlife from several areas of the San Joaquin Valley.

Numerous studies and considerable funds have been dedicated to finding a feasible and acceptable solution to the mutual dilemma of finding a means of drainage water disposal from the irrigated lands of the San Joaquin Valley and of sustaining the 320 000 hectares of irrigated land now being threatened by waterlogging and salinity while simultaneously protecting the water quality of the surface and groundwaters, and remaining associated ecological habitats (largely wildlife refuges) of the region.

This example illustrates the new concern about the environment and ecology that is developing worldwide and the new more holistic approach that must be undertaken to balance developmental, environmental and ecological needs. In the case of the San Joaquin Valley "drainage" problem, the approach being undertaken involves a series of programmes. Firstly, source control through the implementation of more efficient irrigation systems and practices are being undertaken to conserve water and reduce deep percolation. Reuse of the unavoidable drainage waters through a succession of crops of increasing salt tolerance, including eucalyptus and halophyte species, is also being implemented so as to reduce drainage water volumes and conserve water, while producing useful biomass. Conjunctive use of saline groundwater and surface water is being considered to aid in lowering water tables, hence reducing drainage disposal need, and conserving water. Treatment of drainage water and various means of ultimate disposal of the unusable final drainage effluent through deep aquifer injection and ecologically safe evaporation ponds and its release during high stream-flow periods are also under consideration. Lastly, release of freshwater supplies to refuge areas and the retirement of irrigated land deemed the major source of the pollutional problems are also being considered. All of these so-called "in-valley" solutions are being put ahead of the construction of a master drain and ocean disposal in keeping with the philosophy of dealing with the problem at the source and in making the "polluters" pay the costs of pollution that they cause rather than allowing them to discharge their wastes at the expense of others (people, environments and ecological systems).

For more details on the drainage problems and solutions underway in the San Joaquin Valley see Letey *et al.* (1986), and the books edited by Dinar and San Joaquin Valley Drainage Program (1990), Dinar and Zilberman (1991) and the National Research Council (1989).

California is not the only place which has suffered from ecological effects of irrigation. Each year some 3300 $km^3$ of water are removed from the earth's rivers, streams, and groundwater systems to irrigate crops (Postel 1989). Such diversion and redistribution of water has had a profound impact on the earths ecology. Much wetland habitat has been lost due to reduced river and stream flows, surface water supplies have become contaminated with salts and agri-chemicals, groundwater aquifers have been depleted and overlying lands have subsided due to excessive extraction, and fish and fowl have been poisoned by toxic salts released through irrigation and drainage (Postel 1989). The Aral Sea in the central Asian republics of the ex-Soviet Union is another good example. Fully 95 percent of the ex-Soviet Union Republics' cotton harvest is grown in this region, as well as a third of the country's fruits, a quarter of its vegetables and 40 percent of its rice. Ninety percent of these croplands are irrigated. By 1950, the flows of the rivers (Amu Dar'ya and Syr Dar'ya) replenishing the Aral Sea had been reduced to a trickle, the Sea volume reduced by two-thirds and its salinity increased threefold. All native fish species have disappeared. Winds pick up salt from the dry seabed and annually dump 43 million tons on surrounding cropland. The outlook for the Aral Sea and its associated ecology is bleak. Such visible damage from large-scale irrigation has spawned strong opposition to new dams and diversion projects, even in developing countries where irrigation development remains a high priority (Postel 1989).

These problems along with the loss of free-flowing rivers, the destruction of fisheries and damage to riverine and other wildlife habitat must be recognized. Efforts to restore and protect natural ecosystems may require the shifting of some water away from agriculture. The implementation of management practices to conserve water, to reduce deep percolation and the disposal of drainage wastes into good water supplies will go a long way towards sustaining ecology. The reuse of drainage water and the use of saline waters for irrigation will aid appreciably in these matters.

The above examples illustrate the ecological problems and mitigation costs and complexities associated with irrigation and drainage and the potential benefit that the use of saline drainage waters can have as part of the solution to the disposal issue.

## Water-borne Diseases

Irrigation creates an environment that is conducive to the breeding of many vectors of water-borne diseases. Vectors are organisms which transport pathogens from one person (or animal) to another and also provide within themselves an environment for the pathogen to complete part of its life-cycle. The long and unfortunate record of increases in diseases, which are associated with water development in general and irrigation in particular, demonstrates the increased disease vulnerability of a region following the establishment of irrigation schemes. While there is agreement on the potential water-borne disease hazards associated with irrigation developments, it is important to recognize the complementarity of health and irrigation development. Improved nutrition, provision of a good and adequate water supply for domestic use, rural infrastructure, and housing and health facilities, which many irrigation projects bring to rural communities, contribute significantly to good health. Many of the health hazards associated with irrigation development could well be eliminated if the development is approached in a well-planned and integrated manner and environmental management measures are incorporated in the design and management of irrigation projects to safeguard the populations from health hazards.

In this publication, discussion is limited to two important vector transmitted water-borne diseases, mainly malaria and schistosomiasis and their relationships to water quality.

Malaria is by far the most important. At the global level more than two thousand million people are estimated to be at risk; some 240 million are estimated actually to carry the parasite at any given time, and annually an estimated 100 million cases of clinical illness resulting from the infection take place. Vectors of malaria are mosquitoes belonging to the genus *Anopheles* which generally speaking require stagnant or slow-flowing, clean fresh water for their larval development. Exceptionally some species breed by preference in organically polluted or in brackish water.

Schistosomiasis (bilharziasis) is endemic in 76 countries, where about 200 million people are infected with the schistosome parasites. Perhaps more than malaria, which has a rather patchy distribution over time and space, schistosomiasis is generally perceived as directly linked to irrigation schemes and other water resources development projects. The intermediate hosts of the schistosome parasites are aquatic or amphibious freshwater snails with a remarkable tolerance to a number of environmental parameters, but particularly thriving in waters infested by aquatic weeds (which they use as a substrate) and with organic matter.

Physical, chemical and biological parameters of water quality may all influence the suitability of certain water bodies for mosquito and snail breeding. In theory, possible physical parameters include temperature, clarity, viscosity, conductivity, surface tension and, though perhaps not really a physical quality, water current speed. Chemical parameters include the concentrations of various anions and cations, overall salt concentration, pH and the concentration of synthetic compounds. Biological parameters include organic matter, bacterial/fungal/algal contamination of aquatic weeds. Any of the abiotic water quality factors may also indirectly affect vector breeding by favouring certain types of aquatic vegetation (Bos 1991).

As a rule of thumb, *Anopheles* mosquitoes breed in fairly clear, and oxygen rich water. Turbidity, due to organic pollution, results in a diminished light penetration, and at a certain depth anaerobic processes may take over. This, together with eutrophication will considerably lower the oxygen pressure and make the water unsuitable for anopheline breeding. Nevertheless, there are a number of exceptions: *A. kochi, A. vagus, A. barbirostris, A. gambiae* and *A. pharoensis* are all rice field associated mosquitoes that have been observed to breed in turbid water (Lacey and Lacey 1990). For *A. stephensi* in India and *A. arabiensis* in Nigeria similar observations have been made in other habitats (WHO 1982).

The ionic composition and overall salt concentration of water bodies is a crucial chemical parameter for mosquito vectors of malaria. Most anophelines prefer fresh water, but there are some notable exceptions of species with a preference for brackish water: *Anopheles sundaicus* (in South and South East Asia) and *A. aquasalis* (in South America).

There are some notorious malaria epidemics related to sudden changes in salt concentrations in water bodies. An outbreak in the Indonesian village of Brengkok (East Java) in 1933 was attributed to a combination of saline soils and a year with exceptionally low rainfall. The normally rainfed cultivated fields were left fallow and because of the lack of rain the pools turned brackish. This led, in turn, to a population explosion of the malaria vector and an outbreak of malaria (Snellen 1988).

Tidal changes and seasonally varying flow volumes of rivers result in fluctuating salt concentrations in coastal lagoons. This may give rise to seasonal malaria outbreaks, either because one of the brackish water breeding mosquitoes is favoured when salt concentrations are high, or because a freshwater species is temporarily favoured when they are low (e.g. *Anopheles albimanus* in coastal lagoons in El Salvador).

Water chemistry may also have an indirect effect on mosquito populations, when it favours organisms on which larvae feed, or when it affects potential biological control agents of mosquitoes. A study by Pitcairn *et al.* (1987) showed that in Californian rice fields hard (calcium-rich) water favoured the growth of a macrophytic alga, *Chara*, whose presence is positively correlated with the abundance of *Anopheles freeborni* and *Culex tarsalis* larvae.

Mather (FAO 1985) reported that water quality factors may intensify a vector problem or create physical conditions resulting in the problem. He summarized four ways in which water quality may affect the size and species composition of disease vectors and nuisance insects:

- by creating soil conditions which extend water surfaces in area or in duration;
- by requiring irrigation practices which result in the extension of water surfaces in area and duration;
- by modification of aquatic flora and fauna;
- by direct influence on the vector.

In many irrigation schemes, lack of or inadequate surface drainage was found to be a major cause of vector multiplication. Badly constructed drains, as well as poorly maintained ones, create ideal breeding conditions for mosquitoes and aquatic snails. Adoption of good irrigation water management practices and appropriate environmental management measures such as efficient water conveyance, proper irrigation scheduling, improved on-farm irrigation methods, and unimpeded drainage result in a minimum of unnecessary water surface and standing water and thus provide little opportunity for breeding of vectors. In conclusion, it may be said that proper use of saline water for crop production is not likely to contribute any significant increase in the incidence of water-borne diseases.

## IMPACTS OF BLENDING ON WATER USABILITY AND POLLUTION

The ultimate objective of water quality protection should be to permit the maximum practical benefit (use) to be derived from the available water supply. Broadly speaking, users of a water supply may be classified into two groups: those who consume the water in the process of use, and those who use it without appreciable consumption. The first type of users will suffer disbenefit in the "blending" philosophy of water quality protection.

The purpose of this section is to provide evidence - theoretical and conceptual - that the blending approach typically used for water quality enhancement and protection is often deficient for these purposes and to offer an alternative approach for dealing with the "disposal" of saline drainage waters - one that provides a greater practical benefit from the total water supply than blending does.

In considering the use of a saline water for irrigation and in selecting appropriate drainage management to protect water quality, it is important to recognize that the total volume of a saline water supply cannot be beneficially consumed for irrigation and crop production (transpired); the greater its salinity, the less it can be consumed before the concentration becomes limiting. Plants must have access to water of a quality that permits consumption without the concentration of salts (individually or totally) becoming excessive for adequate growth. In the process of transpiration, plants essentially separate nearly pure water from the salt solutions present in the rootzone and these salts are concentrated in the remaining unused soil water. This water ultimately becomes drainage water. A plant will not grow properly when the salt concentration in the soil water exceeds some limit specific to it under the given conditions of climate and management (Bernstein 1975). Thus, it is obvious that not all of the water in a supply can be consumed by a plant, if the water contains salt. The practice of blending or diluting excessively saline waters with good quality water supplies should only be undertaken after consideration is given to how it affects the volumes of consumable water in the combined and separate supplies.

Three case examples are given to illustrate some of the preceding conclusions. In these examples, the factor limiting crop growth is assumed to be the presence of excessive total dissolved salts, but an analogous case could also be made for boron or any other constituent that is specifically toxic to plants. Calculations of the salinity of the soil water resulting within the rootzone were made from knowledge of the salinity of the irrigation water ($EC_{iw}$) and leaching fraction (LF) using the non-computer version of Watsuit. The leaching requirement, $L_r$, was taken to be that value of LF needed to keep the average salinity of the rootzone from exceeding the threshold tolerance level of the crop (the maximum level that the crop can tolerate without loss of yield, $\acute{EC}_e$; a higher value could be used, if some loss of yield can be tolerated). Relative crop yield was calculated from the predicted average soil water salinity, knowledge of the plant tolerance to salinity and the assumption that crops respond to the average salinity within their rootzone. The values of $EC_e$ used were those given in the crop tolerance tables (9 and 10). The fraction of the irrigation water that was consumed in evapotranspiration without yield loss was determined by $V_{et}/V_{iw}$, which was calculated from $L_r$ using the following relation:

$$V_{et} / V_{iw} = (1 - L_r) \qquad (9)$$

In the case examples, the volumes of $V_{iw}$ were normalized by expressing them relative to $V_{et}$, i.e. for the case where $V_{et}$ is taken to be equal to 1.

### *Case 1*

The conditions: use of a "good-quality" water of $EC_{iw} = 0.5$ dS/m for the irrigation of beans ($E\acute{C}_e = 1.0$ dS/m).

This water is judged suitable for the irrigation of beans, since the product ($EC_{iw}$) (Fc) is less than $E\acute{C}_e$ at practical levels of leaching. For example, the predicted level of average salinity within the rootzone resulting from long-term irrigation with this water supply at LF = 0.15 is only 0.75 dS/m (0.5 dS/m x 1.51; the value 1.51 was obtained from Table 27). Beans can tolerate a soil salinity of $E\acute{C}_e = 1.0$ dS/m without any loss in yield using conventional irrigation management (Table 10). The leaching requirement for this case, as obtained from Figure 8 or 12, is even lower, i.e. 0.09. If beans were irrigated at this latter most-efficient level of leaching, the EC of the drainage water ($EC_{dw}$) resulting from irrigation would be 5.55 dS/m (0.5/0.09; $EC_{iw}$/LF). Obviously this latter drainage water could not be used again to grow beans, since the resulting average rootzone salinity could not be kept within acceptable limits at any reasonable level of LF.

### *Case 2*

The conditions: use of the saline drainage water of EC = 5.55 dS/m, as obtained in case 1, for the irrigation of cotton ($E\acute{C}_e = 7.7$ dS/m).

This water which was judged unsuitable for growing beans (see case 1), is quite acceptable for growing cotton, since the predicted level of average rootzone salinity resulting from its use for irrigation is less than the $E\acute{C}_e$ value of cotton at practical levels of leaching. For example, the average $EC_e$ will be less than $E\acute{C}_e$ for any value of LF in excess of 0.17 (see Figure 12 for the case of $F'_c = 7.7/5.5$). When irrigated at LF = 0.17, $EC_e$ will be 7.7 dS/m and $EC_{dw}$ will be 32 dS/m (5.5/0.17).

Thus it is apparent that the saline drainage water of EC = 5.55 dS/m (that resulted from the irrigation of beans with the "good quality" water) could be used satisfactorily to grow salt-tolerant crops like cotton, barley, sugarbeets, etc. It is also true that the drainage volume needing ultimate disposal from the irrigated area would be greatly reduced through its reuse for irrigation within the area. In this case the percent reduction in volume of drainage water ultimately needing to be discharged from the area is 83 (100 - 17; this value can also be calculated using Equation 10, i.e. 1 - 5.55/32). The secondary saline drainage water of EC = 32 dS/m that resulted from the irrigation of cotton obviously cannot be used again to grow more cotton (or sugarbeets, etc.), since excessive yield losses would result. But this water is in a favorable condition for disposal or desalting, i.e. it is in a relatively small volume and at a relatively high salt-concentration.

*Case 3*

The conditions: use of a blend of the "good quality" water (EC = 0.5 dS/m) and the secondary saline drainage water (EC = 32 dS/m) achieved in case 2 from the irrigation of cotton with "bean" drainage water. The blend is made up of 40 units of the "good quality" water and 1 unit of the very saline drainage water; the $EC_{iw}$ of this blend is 1.5 dS/m.

This blended water could be used to grow beans without yield loss since the predicted resulting level of average rootzone salinity can be kept less than $\acute{EC}_e$ (1.0 dS/m), but only by irrigating at a very high and generally impractical level of leaching ($L_r$ = 0.6, as obtained from Figure 12). However, the process of blending has reduced the volume of water in the total supply that can be used by the bean crop (or any other salt-sensitive crop) for transpiration, as shown in the following paragraphs.

The relative volume of irrigation water required to meet ET and to achieve $L_r$ in this case is 2.500 units ($1/1-L_r$). Of this volume, 1.500 units will pass through the rootzone to become drainage water ($V_{dw} = V_{iw} - V_{et}$). Of the 2.500 units of blended irrigation water, 2.439 units (40/41 x 2.500) consist of the "good-quality" water of EC = 0.5 dS/m and 0.061 units (1/41 x 2.500) consist of the secondary saline drainage water of EC = 32 dS/m. Thus, at best, only 0.061 units of the 1.50 units of volume of the drainage water that resulted from irrigating this bean crop with the blended water could possibly have come from the drainage water that was put into this blend. Therefore, the rest (i.e. 1.439 units) must have come from the "good-quality" water component of the blend. This amount of drainage water is much higher than that for the case where only the "good-quality" water of EC = 0.5 dS/m was used to grow the beans (see case 1, where $L_r$ was 0.09, $V_{iw}$ was 1.099 units, and $V_{dw}$ was 0.099 units). A comparison of the results of cases 1 and 2 shows that 127 percent more of the "good-quality" water had to be used to irrigate the bean crop when it was used in the blend (1.401 units more; 2.50 versus 1.099 units) compared to when it was used solely. This is so because 1.401 units of the good-quality water was made unavailable for transpiration by the bean crop without loss in yield, through the blending process. Also as a result of blending, the volume of required drainage was increased substantially (1.500 versus 0.099 units). Such excessive drainage may cause other problems, such as increase in area affected by waterlogging in the project, in the loss of nutrients through excessive leaching, etc.

Another way to illustrate that a loss of usable water in the total supply has occurred as a consequence of this blending is to contrast the relative fraction of the "good-quality" water supply that could be used to grow beans (i.e. could be used for transpiration) with and without blending. For this purpose, assume that the volume of the good-quality water of EC = 0.5 dS/m is 100 units. Without blending all but 9 units, i.e. 91 units, ((100 - $V_{dw}$, or (100) - (100)(.09)) can be consumed in ET. However, when saline drainage water of EC = 32 dS/m is blended with this 100 units of "good-quality" water in the ratio of 40 to 1 to give a larger total supply of 102.5 units (for which $L_r$ is 0.6 and $V_{dw}$ is 61.5 units), only 41 units (102.5 - 61.5) are usable for ET by beans without loss of yield. Thus, 50 units (91 - 41) of the original 100 units of "good-quality" water were made unusable for the production of beans by adding saline water of EC = 32 dS/m to it in the ratio of 1:40.

The results of these case-studies clearly show that adding saline waters to good quality water supplies can reduce the volume of the good-quality water supply that could be consumed by salt-sensitive crops. The amount of such reduction will depend upon the relative volumes and concentrations of the receiving and waste waters and upon the tolerances of the crops to be irrigated. The significance of such losses of usable water through blending will depend upon a number of factors, especially upon the salt sensitivity of the crop to be grown with the blended water and the relative concentrations and volumes of the drainage and receiving waters. Therefore the merits of blending should be evaluated on a case-by-case basis. The case of a hypothetical river system receiving drainage return is discussed elsewhere (Rhoades 1989; Rhoades and Dinar 1990). This case study showed that the pollution of rivers that occurs through the return of drainage waters can be avoided by intercepting the drainage return flows, reusing them for irrigation and isolating the ultimate unusable drainage from any good quality water supply.

In the previously discussed case studies, it was assumed that the fraction of water usable for crop production was limited by $\acute{EC}_e$. Obviously, more water use can be achieved, if some loss of yield is permitted. When the growth-limiting factor is salinity, the ultimate fraction of water in a supply that can be used in crop growth is:

$$\textit{Fraction of water used in crop growth} = 1 - \frac{EC_{iw}}{EC_m} \qquad (10)$$

where $EC_{iw}$ is the electrical conductivity (concentration can be used alternatively) of the water supply and $EC_m$ is the maximum electrical conductivity (concentration, etc.) of the water in the rootzone (on a soil water basis; essentially $EC_{dw}$) the plant can tolerate (i.e. draw water from and still yield about 85 - 100 percent). Values of $EC_m$ vary among the crop species, but typically they are (according to Bernstein 1975) about 45 for such tolerant crops as cotton, sugarbeets, barley, 30 for intermediate crops like, tomatoes, wheat and alfalfa, and about 15 for sensitive crops, like beans, clovers and onions. In some cases, it may make economic sense to blend and to bear the consequences of the losses of water usability and of crop yield when the alternative costs of disposal are much more costly.

Sometimes drainage waters are purposely diluted with a "good-quality" water to meet some specified discharge standard (say an EC of 1.5 dS/m, as resulted in case 3) and then returned to a "good-quality" water supply. For example (as in case 3), 1 unit of drainage water of EC = 32 dS/m could be blended with 40 units of water of EC = 0.5 dS/m and then the 41 units of blended water of EC = 1.5 dS/m returned to the major water supply of good quality. But as the above-described results showed, even when such a relatively small volume of such blended water is incorporated into the larger "good-quality" water supply, the net result is that a fraction of this latter water is made unusable for transpiration by salt-sensitive crops (such as beans) without loss of yield. In the case described above, 50 units out of every 100 units in the large supply will be made unusable for each 1 unit of drainage volume added to it. Thus it is concluded that blending or diluting drainage waters with good quality waters in order to increase water supplies or to meet discharge standards may be inappropriate under certain situations. Even though the concentration of the blend may appear to be low enough to be acceptable by conventional standards, the usability of the good-quality water supply for growing salt-sensitive crops (or for other salt-sensitive water uses) may be reduced through the process of blending. Each time the salt content of an agricultural water supply is increased, the degree to which it can be consumed before its concentration becomes excessive and limiting is decreased. More crop production can usually be achieved from the total water supply by keeping the water components separated. Serious consideration should be given to keeping saline drainage waters separate from the "good-quality" water supplies, especially when the latter waters are to be used for irrigation of salt-sensitive crops. The saline drainage waters can be used more effectively by substituting them for "good-quality" water to irrigate certain crops grown in the rotation after seedling establishment. Reuse of drainage water for irrigation of suitably salt-tolerant crops reduces the volume of drainage water needing ultimate disposal and the off-site pollution problems often associated with the discharge of irrigation return flows.

# Chapter 6

# Management principles and practices for safe use of saline water

While irrigated agriculture has greatly increased crop productivity, inappropriate and inefficient irrigation has wasted water, polluted surface water and groundwater, damaged productivity and altered the ecology of vast areas of land. Contamination of water supplies by irrigation is, in many places, posing health risks and drastically increasing the costs of treating waters for domestic and industrial uses. Surface and groundwaters in many areas are being contaminated by salts, fertilizers, herbicides and pesticides. Toxic chemicals are rendering many developed water supplies unfit for drinking and even for irrigation in some cases. These pollutants also degrade the recreational use and esthetic value of surface waters. At the same time, costly limitations are being placed upon irrigation to reduce its pollutional discharges or to treat its wastes before discharge. Finding a suitable, acceptable place for such discharge is increasingly becoming a major problem in some situations, especially in the developed countries. Blending saline and fresh waters reduces the potential usability of the total water supply. Use of polluted waters for irrigation limits crop production potential, as well as posing some potential health hazards to the consumers of the food.

To overcome the above-described problems, new techniques need to be developed and implemented to reduce excessive water uses and to conserve limited water supplies and better ways must be found to implement existing methods more effectively. Efficiency of irrigation must be increased by the adoption of appropriate management strategies, systems and practices and through education and training. Reuse of wastewater, including the use of drainage water and shallow saline groundwater for crop production, must be made an integral component of irrigation water management, water conservation and environmental protection programmes. Effective salinity control measures must be implemented to sustain irrigated agriculture and to prevent pollution of associated water resources. Such measures must be chosen with recognition of the natural processes operative in irrigated, geohydrologic systems, not just those on-farm, and with an understanding of how they affect the quality of soil and water resources, not just crop production. Some practices can be used to control salinity within the crop rootzone, while other practices can be used to control salinity within larger units of management, such as irrigation projects, river basins, etc. Additional practices can be used to protect off-site environments and ecological systems - including the associated surface and groundwater resources. The "on-farm" practices usually consist of agronomic and engineering techniques applied by the farmer on a field-by-field basis. The "district-wide" or "larger organizational basis" practices generally consist primarily of engineering structures for water control (both delivery and discharge) and systems for the collection, reuse, treatment and/or disposal of drainage waters.

There is usually no single way to achieve safe use of saline water in irrigation. Many different approaches and practices can be combined into satisfactory saline water irrigation systems; the appropriate combination depends upon economic, climatic, social, as well as edaphic and hydrogeologic situations. Thus, no procedures are given here for selecting "the" appropriate set of practices for different situations. Rather, some important goals, principles and strategies of water, soil and crop management practices that should be considered in the use of saline water for irrigation are presented as guidelines.

## MANAGEMENT GUIDING PRINCIPLES

Salinity management constitutes an important aspect of safe use of saline water irrigation. This requires an understanding of how salts affect plants and soils, of how hydrogeologic processes affect salt accumulation, and also of how cropping and irrigation activities affect soil and water salinity. The basic effects of salts on soils and plants and the major causes and processes of salinization in irrigated lands and associated water resources that must be understood in order to develop and implement effective control practices were discussed in chapters 4 and 5.

To prevent the excessive accumulation of salt in the rootzone from irrigation, extra water (or rainfall) must, over the long term, be applied in excess of that needed for ET and must pass through the rootzone in a minimum net amount. This amount, in fractional terms, is referred to as the "leaching requirement" ($L_r$, the fraction of infiltrated water that must pass through the rootzone to keep salinity within acceptable levels; US Salinity Laboratory Staff 1954). In fields irrigated to steady-state conditions with conventional irrigation management, the salt concentration of the soil water is essentially uniform near the soil surface regardless of the leaching fraction (LF, the fraction of infiltrated water that actually passes through the root-zone) but increases with depth as LF decreases. Likewise, average rootzone salinity increases as LF decreases; crop yield is decreased when tolerable levels of salinity are exceeded. Methods to calculate the leaching requirement and to predict crop yield losses due to salinity effects were described previously. Once the soil solution has reached the maximum salinity level compatible with the cropping system, at least as much salt as is brought in with additional irrigations must be removed from the rootzone; a process called "maintaining salt balance."

To prevent waterlogging and secondary salination, drainage must remove the precipitation and irrigation water infiltrated into the soil that is in excess of crop demand and any other excessive water (surface or subsurface) that flows into the area; it must provide an outlet for the removal of salts that accumulate in the rootzone in order to avoid excessive soil salinization, and it must keep the water table sufficiently deep to permit adequate root development, to prevent the net flow of salt-laden groundwater up into the rootzone by capillary forces and to permit the movement and operation of farm implements in the fields. Artificial drainage systems may be used in the absence of adequate natural drainage. They are essentially engineering structures that control the water table at a safe level according to the principles of soil physics and hydraulics. The water table depth required to prevent a net upward flow of water and salt into the rootzone is dependent on irrigation management and is not single-valued as is commonly assumed (van Schilfgaarde 1976). Methods to calculate drainage requirements are given elsewhere (Rhoades 1974; Kruse *et al.* 1990; Hoffman *et al.* 1990).

As discussed earlier, the time-averaged level of rootzone salinity is affected by the degree to which the soil water is depleted between irrigations, as well as by the leaching fraction.

As the time between irrigations is increased, soil water content decreases as the soil dries, and the matric and osmotic potentials of the soil water decrease as salts concentrate in the reduced volume of water. Water uptake and crop yield are closely related to the time and depth averaged total soil water potential, i.e. matric plus osmotic. As water is removed from a soil with non-uniform salinity distribution, the total water potential of the water being absorbed by the plant tends to approach uniformity in all depths of the rootzone. Following irrigation, plant roots preferentially absorb water from rootzone depths with high water potential. Normally this means that most of the water uptake is initially from the upper, less saline soil depths until sufficient water is removed to increase the total water stress to a level equal to that in the lower depths. After that water is removed from the deeper, more saline soil depths and the effect of salinity, *per se*, on crop growth is magnified. This implies that:

- forms of irrigation that minimize matric stress, such as drip irrigation, can be used to minimize the harmful effects of irrigating with saline water;

- high leaching fractions can be used to minimize the buildup (hence harmful effects) of high levels of salinity in deeper regions of the rootzone.

The distribution within and the degree to which a soil profile becomes salinized are also functions of the manner of water application, as well as the leaching fraction. More salt is generally removed per unit of leachate with sprinkler irrigation than with flood irrigation. Thus, the salinity of water applied by sprinkler irrigation can be somewhat higher, all else being equal, than that applied by flood or furrow irrigation with a comparable degree of cropping success, provided foliar burn is avoided. The high salt-removal efficiency of sprinkler irrigation may be explained as follows. Solute transport is governed by the combined processes of convection (movement of solutes with the bulk solution) and diffusion (independent movement of solutes as driven by a concentration gradient); convection is usually the predominant process in flood-irrigated soils. Differential velocities of water flow can occur within the soil matrix because the pore size distribution is typically non-uniform. This phenomenon is called dispersion. It can be appreciable when flow velocity is high and pore size distribution is large; diffusion often limits salt removal under such conditions. Soils with large cracks and well-developed structure are especially variable in their water and solute transport properties because the large "pores" are preferred pathways for water flow, as are earthworm channels, old root holes, interpedal voids, etc.; most of the flow in flooded soils occurs via these "pores". Much of the water and salt in the small and intra-aggregate pores is "bypassed" in flood irrigated soils. Flow velocity and water content are typically lower in soils irrigated with sprinklers; hence, bypass is reduced and efficiency of salt leaching is increased. Other soil-related processes also affect salt concentration and transport during the irrigation and leaching of soils. In most arid land soils, the clay particles are dominated by negative charges, which can retard cation transport through adsorption and/or exchange processes. Simultaneously, anions are largely excluded from that part of the pore solution adjacent to the negatively-charged clay surface; this accelerates their relative transport. The borate anion also undergoes adsorption reactions that retard its movement. For a more quantitative description of effects of convection and dispersion and other soil factors on solute transport in soils see the review of Wagenet (1984).

The distribution of salts in the soil is also influenced by seedbed shape. Salts tend to accumulate to excess levels in certain regions of the seedbed under furrow irrigation (Bernstein *et al.* 1955; Bernstein and Fireman 1957). Information from this early study shows that seedbed and furrow shape can be designed to minimize this problem. Seed placement and surface irrigation strategies (e.g. alternative furrow, depth of water in furrows, etc.) that can also be used to optimize plant establishment under saline conditions are described by Kruse *et al.* (1990). Sprinkler irrigation can be effective in leaching excessive salinity from the top-soil and in producing a favourable low-salinity environment in the upper soil layer which is necessary for the establishment of salt-sensitive seedings. However, other problems (such as foliar injury) are associated with sprinkling of saline water. Saline, "bed-peaks" can be detopped to prevent exposure to emerging shoots. Under drip irrigation, the salt content is usually lowest in the soil immediately below and adjacent to the emitters and highest in the periphery of the wetted zone. Removal of salt that has accumulated in this wetting zone "front" must be addressed in the long-term.

Susceptible crops should not be irrigated with saline water by sprinkler irrigation since their foliage absorbs salts upon wetting. Salts can accumulate in leaves by foliar absorption of such crops until lethal concentrations have been reached. Crop sensitivity to saline sprinkling water is related more to the rate of foliar salt accumulation than to crop tolerance to soil salinity, *per se*. Hence, applications should be made during the night and in a manner to achieve frequent wetting ("washing") of the leaves in order to minimize foliar absorption of salts when irrigating with saline waters by sprinkler methods.

The prevalent models of solute reactions and transport in irrigated soils suffer the deficiency of not appropriately representing the effects of the above-described processes that often occur under field conditions. Neither do they adequately account for the distribution uniformity effects of the irrigation application system itself, or of the infiltration uniformity effects resulting from variable soil permeability across the field. Only recently has this problem been approached directly by measuring, on a large scale, solute distributions in field soil profiles. The results to date indicate that as yet no suitable method to quantify and integrate the effects of these processes on a field basis exists (Jury 1984). It is probable that alternative modelling approaches, like that proposed by Corwin and Waggoner (1990), may help in this regard.

Some unique effects of irrigation are operative at the scale of whole projects and entire geohydrologic systems; hence, some management practices for salinity control should address this larger scale. The following paragraphs provide a brief review of such information, as a basis for determining appropriate management requirements for irrigating with saline water.

As discussed earlier, some soil and water salination is inevitable with irrigation; the salt contained in the irrigation water remains in the soil as the pure water passes back to the atmosphere through the processes of evaporation and plant transpiration. Therefore, water in excess of evapotranspiration must be applied with irrigation to achieve leaching and prevent excess salt accumulation. This water must drain from the rootzone. Seepage from delivery canals also occurs in many irrigation projects. These drainage and seepage waters percolate through the underlying strata (often dissolving additional salts in the process), flow to lower elevation lands or waters and frequently cause problems there of waterlogging and salt-loading. Saline soils typically are formed in such lands through the processes of evaporation. Ground and surface waters receiving these drainage and seepage waters typically are increased in salt concentration.

The primary sources of return flow from an irrigation project are bypass water, canal seepage, deep percolation, and surface (tailwater) runoff. Bypass water is often required to maintain hydraulic head and adequate flow through a gravity-controlled canal system. It is usually returned directly to the river, and few pollutants, if any, are picked up in this route. Evaporation losses from canals commonly amount to only a small percentage of the diverted water. Seepage from unlined canals is often substantial. It may contribute to high water tables, increase groundwater salinity and phreatophyte growth, and generally increases the amount and salinity of the required drainage from irrigated areas. Law *et al.* (1972) estimated that 20 percent of the total water diverted for irrigation in the USA is lost by seepage from conveyance and irrigation canals. If the water passes through salt-laden substrata or displaces saline groundwater, the salt pickup from this source can be substantial. Canal lining can reduce such salt loading. Closed conduit conveyance systems can minimize both seepage and evaporation losses and ET by phreatophytes. The closed conduit system also provides the potential to increase project irrigation efficiency and to thus lower salt loading (van Schilfgaarde and Rawlins 1980).

Reducing the volume of water applied for irrigation proportionately reduces the amount of salt added and the amount needed to be removed by leaching. Minimizing the leaching fraction maximizes the precipitation of applied Ca, $HCO_3$, and $SO_4$ salts as carbonates and gypsum minerals in the soil, and it minimizes the "pickup" of weathered and dissolved salts from the soil. The salt load from the rootzone can be reduced from about 2 to 12 tons/ha per year by reducing LF from 0.3 to 0.1 (Rhoades *et al.* 1973; 1974; Rhoades and Suarez 1977; Oster and Rhoades 1975).

Minimizing leaching may or may not reduce salinity degradation of the receiving water where the drainage water is not intercepted and isolated and is returned to the associated surface or groundwater. A reduction of degradation will generally occur where saline groundwaters with concentrations in excess of those of the recharging rootzone drainage waters are displaced into the surface water or where additional salts, other than those derived from the irrigation water, are encountered in the drainage flow path and brought into solution by weathering and dissolution processes.

Groundwaters receiving irrigation drainage water may not always benefit from reduced leaching. With no sources of recharge other than drainage return flow, the groundwater eventually must come to the composition of the drainage water, which will be more saline with low leaching. Reduced leaching slows the arrival time of the leachate. Thus, the groundwater salinity may be lower with reduced leaching for an interim period of time (Rhoades and Suarez 1977; Suarez and van Genuchten 1981). For groundwater under-saturated with $CaCO_3$ (unlikely in arid lands) being pumped for irrigation with no recharge other than by drainage return, groundwater will be slightly less saline under low leaching; groundwater saturated with $CaCO_3$ will show no benefit under low leaching; and groundwater saturated with $CaCO_3$ and nearing saturation with gypsum will show substantial benefit from low leaching. Low leaching management can continuously reduce degradation of the groundwater, only if other sources of high-quality recharge into the basin exist and if flow out of the basin is high relative to drainage inflow.

The extent to which leaching can be minimized is limited by the salt tolerances of the crops being grown, the irrigation system distribution uniformities and the variability in soil infiltration rates. In most irrigation projects, the currently used leaching fractions can be reduced appreciably without harming crops or soils, especially with improvements in irrigation management (van Schilfgaarde *et al.* 1974).

## MANAGEMENT FOR CROP PRODUCTION

Management practices for the safe use of saline water for irrigation primarily consist of:

- selection of crops or crop varieties that will produce satisfactory yields under the existing or predicted conditions of salinity or sodicity;

- special planting procedures that minimize or compensate for salt accumulation in the vicinity of the seed;

- irrigation to maintain a relatively high level of soil moisture and to achieve periodic leaching of the soil;

- use of land preparation to increase the uniformity of water distribution and infiltration, leaching and removal of salinity;

- special treatments (such as tillage and additions of chemical amendments, organic matter and growing green manure crops) to maintain soil permeability and tilth. The crop grown, the quality of water used for irrigation, the rainfall pattern and climate, and the soil properties determine to a large degree the kind and extent of management practices needed.

### Growing Suitably Tolerant Crops

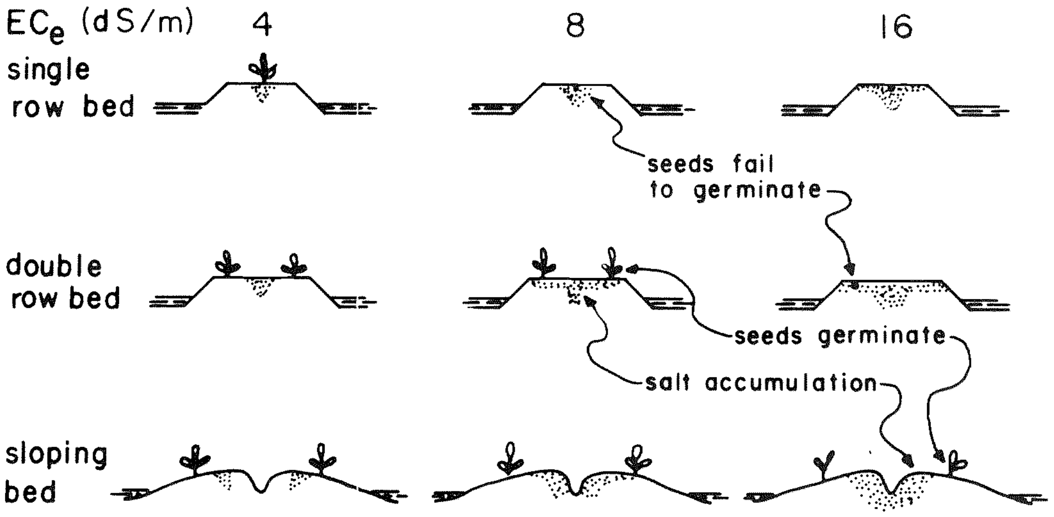
Where salinity cannot be kept within acceptable limits by leaching, crops should be selected that can produce satisfactory yields under the resulting saline conditions. In selecting crops for saline soils, particular attention should be given to the salt tolerance of the crop during seedling development, because poor yields frequently result from failure to obtain a satisfactory stand. Some crops that are salt tolerant during later stages of growth are quite sensitive to salinity during early growth. Tolerances of the various major crops to salinity are given in Tables 13 to 21.

### Managing Seedbeds and Grading Fields to Minimize Local Accumulations of Salinity

Failure to obtain a satisfactory stand of furrow-irrigated row crops on moderately saline soils is a serious problem in many places. This is because the rate of germination is reduced by excessive salinity, as previously discussed. The failures are usually due to the accumulation of soluble salt in raised beds that are "wet-up" by furrow irrigation. Modifications in irrigation practice and bed shape should be used to reduce salt accumulation near the seed. The tendency of salts to accumulate near the seed during irrigation is greatest in single-row, round-topped beds (see Figure 15).

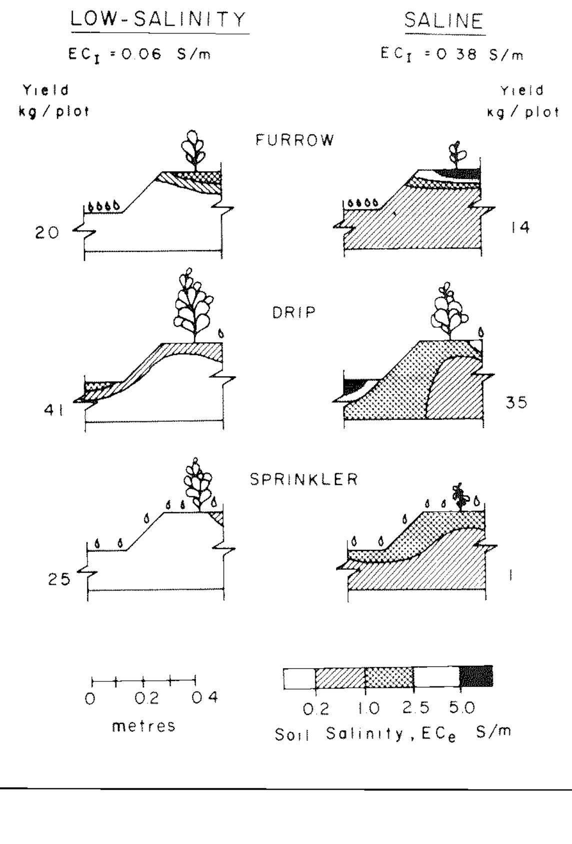
Sufficient salt to prevent germination may concentrate in the seed zone even if the average salt content of the soil is moderately low. Thus, such beds should be avoided when irrigating with saline waters using furrow methods, though "decapping" techniques may be used to advantage in this regard. With double-row, flat-topped beds, since most of the salt moves into the centre of the bed, the shoulders are left relatively free of salt, thus seedling establishment may be enhanced by planting on the shoulders of such beds. Sloping beds are best for saline conditions because the seed can be safely planted on the slope below the zone of high salt accumulation. Such beds should be used, if possible, when furrow irrigating with saline waters. Planting in furrows or basins is satisfactory from the standpoint of salinity control but is often unfavourable for the emergence of many row crops because of problems related to crusting and poor aeration. This method is recommended only for the use of very saline

FIGURE 15
Pattern of salt build-up as a function of seed placement, bedshape and level of soil salinity (after Bernstein, Fireman and Reeve 1955)




irrigation waters and vigorous, hardy emerging plants. Pre-emergence irrigation by use of sprinklers or special furrows placed close to the seed may be used to keep the soluble salt concentration low in the seedbed during germination and seedling establishment (see Figure 16, after Bernstein and Francois 1973). After the seedlings are established, the special furrows may then be abandoned and new furrows made between the rows, and sprinkling replaced by furrow irrigation.

FIGURE 16
Influence of the irrigation system on the soil salinity pattern and yield of bell pepper at two levels of irrigation water quality




Careful grading of land makes possible a more uniform application of water and, hence, better salinity control when irrigating with saline water. Barren or poor areas in otherwise productive fields are often either high spots that do not receive enough water for good crop growth or for leaching purposes or low spots that remain too wet for seedling establishment. Lands that have been irrigated one or two years after initial grading usually need to be regraded to remove the surface unevenness caused by the settling of fill material. Annual crops should be grown after the first grading so that regrading can be performed before a perennial crop is planted. A prior detailed topographic survey could be very helpful to avoid ruining soil properties and in particular removing the surface soil which may be relatively more fertile. Land levelling causes a significant soil compaction due to the weight of the heavy equipment and it is advisable to follow this operation with subsoiling, chiselling and ploughing to break up the compaction and restore or improve water infiltration.

## Managing Soils under Saline Water Irrigation

Several physical, chemical and biological soil management measures help facilitate the safe use of saline water in crop production. Some important ones in this regard are: tillage, deep ploughing, sanding, use of chemical amendments and soil conditioners, organic and green manuring and mulching.

**Tillage** is a mechanical operation that is usually carried out for seedbed preparation, soil permeability improvement, to break up surface crusts and to improve water infiltration. If tillage is improperly executed, it might form a plough layer or bring a salty layer closer to the surface. Sodic soils are especially subject to puddling and crusting; they should be tilled carefully and wet soil conditions avoided. Heavy machinery traffic should also be avoided. More frequent irrigation, especially during the germination and seedling stages, tends to soften surface crusts on sodic soils and encourages better stands.

**Deep ploughing** refers to depths of ploughing from about 40 to 150 cm. It is most beneficial on stratified soils having impermeable layers lying between permeable layers. In sodic soils, deep ploughing should be carried out after removing and reclaiming the sodicity, otherwise it will cause complete disturbances and collapse of the soil structure. Deep ploughing to 60 cm loosens the aggregates, improves the physical condition of these layers, increases soil-water storage capacity and helps control salt accumulation when using saline water for irrigation. Crop yields can be markedly improved by ploughing to this depth every three or four years. The selection of the right plough types (shape and spacings between shanks), sequence, ploughing depth and moisture content at the time of ploughing should provide good soil tilth and improve soil structure (Mashali 1989). Special equipment can even invert whole soil profiles or break up substrata as deep as 2.5 m that impede deep percolation, so that many adverse physical soil conditions associated with land irrigated with saline water can be modified in order to improve leachability and drainability.

**Sanding** is used in some cases to make a fine textured surface soil more permeable by mixing sand into it, thus a relatively permanent change in surface soil texture is obtained. When properly done, sanding results in improved root penetration and better air and water permeability which facilitates leaching by saline sodic water and when surface infiltration limits water penetration. The method can be combined with initial deep ploughing.

**Chemical amendments** are used to neutralize soil reaction, to react with calcium carbonate and to replace exchangeable sodium by calcium. This decreases the ESP and should be followed by leaching for removal of salts derived from the reaction of the amendments with sodic soils. They also decrease the SAR of irrigation water if added in the irrigation system. Gypsum is by far the most common amendment for sodic soil reclamation, particularly when using saline water with a high SAR value for irrigation. Calcium chloride is highly soluble and would be a satisfactory amendment especially when added to irrigation water. Lime is not an effective amendment for improving sodic conditions when used alone but when combined with a large amount of organic manure it has a beneficial effect. Sulphur too can be effective; it is inert until it is oxidized to sulphuric acid by soil micro-organisms. Other sulphur-containing amendments (sulphuric acid, iron sulphate, aluminium sulphate) are similarly effective because of the sulphuric acid originally present or formed upon microbial oxidation or hydrolysis.

The choice of an amendment for a particular situation will depend upon its relative effectiveness judged from its improvement of soil properties and crop growth, the availability of the amendments, relative cost involved, handling and application difficulties and time allowed and required for the amendment to react in soil and effectively replace adsorbed sodium.

Attempts have been made to coagulate soil particles and provide deep aeration and better permeability and water infiltration by chemical treatment. Treating the soil with dilute bituminous emulsions can result in effective aggregation, improved aggregate stability and reduced surface crust formation. Water percolation rate is faster in bitumen-treated soil.

Sulphate lignin conditioner can also be used to improve soil structure, and to improve soil permeability. Soil conditioners can have practical applications in seedling establishment when soil is irrigated with saline water of high SAR. Stability of soil aggregates prevents dispersion and formation of deposit crusts and infiltration can be maintained by application of small quantities of organic polyelectrolytes to the soil surface. They can be effective when introduced in the irrigation water or when sprayed over the soil surface.

**Mineral fertilizers**: Salt accumulation affects nutrient content and availability for plants in one or more of the following ways: by changing the form in which the nutrients are present in the soil; by enhancing loss of nutrients from the soil through heavy leaching or, as in nitrogen, through denitrification, or by precipitation in soil; through the effects of non-nutrient (complementary) ions on nutrient uptake; and by adverse interactions between the salt present in saline water and fertilizers, decreasing fertilizer use efficiency.

Crop response to fertilizer under saline or sodic conditions is complex since it is influenced by many soil, crop and environmental factors. The benefits expected from using soil management measures to facilitate the safe use of saline water for irrigation will not be realized unless adequate, but not excessive, plant nutrients are applied as fertilizers. The level of salinity may itself be altered by excess fertilizer application as mineral fertilizers are for the most part soluble salts. The type of fertilizer applied, when using saline water for irrigation, should preferably be acid and contain Ca rather than Na taking into consideration the complementary anions present. Timing and placement of mineral fertilizers are important and unless properly applied they may contribute to or cause a salinity problem.

**Organic and green manures and mulching**: Incorporating organic matter into the soil has two principal beneficial effects of soils irrigated with saline water with high SAR and on saline sodic soils: improvement of soil permeability and release of carbon dioxide and certain organic acids during decomposition. This will help in lowering soil pH, releasing calcium by solubilization of $CaCO_3$ and other minerals, thereby increasing $EC_e$ and replacement of exchangeable Na by Ca and Mg which lowers the ESP. Growing legumes and using green manure will improve soil structure. Green manure has a similar effect to organic manure. Salinization during fallowing may be severe where a shallow water table exists, since evaporation rates of about 8, 3 and 1 mm/day could occur from the dry surface of fine sandy loam when the water table is kept at 90, 120 and 180 cm from the soil surface, respectively. Mulching to reduce evaporation losses will also decrease the opportunity for soil salinization. When using saline water where the concentration of soluble salts in the soil is expected to be high in the surface, mulching can considerably help leach salts, reduce ESP and thus facilitate the production of tolerant crops. Thus, whenever feasible, mulching to reduce the upward flux of soluble salts should be encouraged.

## Operating Delivery Systems Efficiently

Water delivery and distribution systems must be operated efficiently to facilitate the timely supply of water in the right quantities and to avoid waterlogging and salinity build-up in irrigated lands, especially when saline waters are involved. The amount of water applied should be sufficient to supply the crop and satisfy the leaching requirement but not enough to overload the drainage system. Over-irrigation contributes to the high water table, increases the drainage requirement and is a major cause of salinity build-up in many irrigation projects of the world. Therefore, a proper relation between irrigation, leaching, and drainage must be maintained in order to prevent irrigated lands from becoming excessively waterlogged and salt-affected.

Often irrigation water delivery and distribution systems are over-designed, in the absence of reliable data or appropriate methods to predict project water requirements. It is all the more important, when using saline waters, that excessive amounts are not diverted into irrigation schemes as this is likely to cause more damage than excessive amounts of "good quality" water. FAO has developed methods to determine project water requirements based on actual crop water needs, leaching requirements and irrigation efficiencies (FAO 1984).

A computer program, called CROPWAT (FAO 1992) has been developed to calculate crop water requirements and irrigation requirements from climatic and crop data. Further, the program allows the development of irrigation schedules for different management conditions and the calculation of scheme water supply for varying cropping patterns. The program runs on any standard personal computer with a minimum of 360 Kb of memory. The program can be obtained from FAO on request. A complementary computerized database program called CLIMWAT (FAO 1991) is available to obtain the required climatic data for CROPWAT. CLIMWAT has data from a total of 3262 meteorological stations from 144 countries.

Excessive loss of irrigation water from canals constructed in permeable soil is a major cause of high water tables and secondary salination in many irrigation projects. Such seepage losses should be reduced by lining the canals with impermeable materials or by compacting the soil to achieve a very low permeability. Because the amount of water passing critical points in the irrigation delivery system must be known in order to provide water control and to achieve high water-use efficiency, provisions for effective flow measurement should be made. Unfortunately, many current irrigation systems do not use flow measuring devices and, thus, the farmers operate with limited control and knowledge of the amount of water actually diverted to the farms. In addition, many delivery systems encourage over-irrigation because water is supplied for fixed periods, or in fixed amounts, irrespective of seasonal variations in on-farm needs. Salinity and water table problems are often the result. The distribution system should be designed and operated so as to provide water on demand and in metered amounts as needed to achieve high efficiency and to facilitate salinity control and the use of saline waters for irrigation.

## Irrigating Efficiently

Improvements in salinity control generally come hand-in-hand with improvements in irrigation efficiency. The key to the effective use of saline irrigation waters and salinity control is to provide the proper amount of water to the plant at the proper time. The ideal irrigation scheme should provide water as nearly continuously as possible, though not in excess, as needed to keep the soil water content in the rootzone within optimum safe limits. However, carefully programmed periods of stress may be needed to obtain maximum economic yield with some crops; cultural practices also may demand occasional periods of dry soil. Thus, the timing and amount of water applied to the rootzone should be carefully controlled to obtain good water use efficiency and good crop yield, especially when irrigating with saline water. As mentioned above, this requires water delivery to the field on demand which, in turn, requires the establishment of close coordination between the farmer and the entity that distributes the water; it calls for the use of feedback devices to measure the water and salt contents and potentials in the soil and devices to measure water flow (rates and volumes) in the conveyance systems.

The method and frequency of irrigation and the amount of irrigation water applied may be managed to control salinity. The main ways to apply water are basin flooding, furrow irrigation, sprinkling, subirrigation, and drip irrigation. Flood irrigation is good for salinity control when using saline waters if the land is level, though aeration and crusting problems may occur. Aeration and crusting problems are minimized by using furrow irrigation, but salts tend to accumulate in the beds. If excess salt does accumulate, a rotation of crops and periodic irrigation by sprinkler or flooding should be used as salinity-control measures. Alternatively, cultivation and irrigation depths should be modified, once the seedlings are well established, to "shallow" the furrows so that the beds will be leached by later irrigations. Irrigation by sprinkling may give better control of the amount and distribution of water; however, the tendency is to apply too little water by this method, and leaching of salts beyond the rootzone may sometimes be accomplished only with special effort. Salinity can be kept low in the seedbed during germination with sprinkler-irrigation, but crusting may be a problem. Emergence problems associated with such crusting may be overcome with frequent light irrigations during this time or by use of special tillage techniques. Subirrigation with saline water is not generally advisable unless the soil is periodically leached of the accumulated salts by rainfall or by surface applications of low-salinity water. Drip irrigation, if properly designed, is recommended for use of saline irrigation water because it minimizes salinity and matric stresses in the rootzone, though salts accumulate in the periphery of the wetted area. As noted earlier, higher levels of salinity in the irrigation water can be tolerated with drip as compared with other methods of irrigation.

Because soluble salts reduce the availability of water in almost direct proportion to their total concentration in the soil solution, irrigation frequency should be increased so that the moisture content and salinity of irrigated soils are maintained as high and low, respectively, as is practicable, especially during seedling establishment and the early stage of vegetative growth, if it can be done without resulting in excessive leaching or insufficient depth of rooting. The most practical way to accomplish this is through use of drip irrigation.

Additional water (over that required to replenish losses by plant transpiration and evaporation) must be applied, at least occasionally, to leach out the salt that has accumulated during previous irrigations. This leaching requirement depends on the salt content of the irrigation water and on the maximum salt concentration permissible in the soil solution which depends in turn on the salt tolerance of the crop and the manner of irrigation. If there is insignificant rainfall and irrigation is undertaken with a single water to steady-state, the leaching requirement can be estimated from the relations given in Figure 12. Fortunately, much of the needed leaching can be achieved between crops or during pre-irrigation and early growth-stage irrigations when soil permeability is generally relatively high, especially when using low-salinity waters in the cyclic use strategy. The first irrigations provided for the renewal of cropping following a fallow or uncropped period often unavoidably result in relatively high leaching. Many irrigation practices, especially with flood irrigation, inadvertently result in excess leaching, especially during pre-plant or early-season irrigations before the soil aggregation has slaked and surface soil permeability has diminished. Effects of non-uniform crop stand and cover, soil infiltration rates (permeabilities) and water application and distribution result in generally non-uniform leaching across an irrigated field. Calculation of the leaching requirement is disproportionately subject to errors related to uncertainties in knowledge of evapotranspiration, since $L_r = 1 - V_{et}/V_{iw}$. The value, much less the distribution, of evapotranspiration is not precisely known for most field situations, especially for conditions of irrigation with saline waters and in the presence of shallow, saline water tables. Consequently, there is little documented evidence of the positive benefits of increased leaching on crop yield under actual field conditions when irrigating with saline waters (Shalhevet 1984). While, certainly, the excess salts applied with saline irrigation waters must be removed over time to sustain crop production, for both short- and long-season crops it is generally sufficient to intentionally apply extra water for leaching only if and when the levels of salinity in the active rootzone actually become excessive. Giving extra water for leaching according to traditional $L_r$ equations with each and every irrigation is not necessary. Rainfall in sub-humid climates often provides the required leaching. The control of salinity by leaching is accomplished most easily in permeable coarse-textured soils. Medium- and fine-textured soils have the agronomic advantage of a greater water-holding capacity and ordinarily present no major problem from the stand-point of irrigating with saline water and salinity control, particularly if they have good structure and are underlain by a sand or gravel aquifer which facilitates the removal of drainage water. Prevention of excessive salt accumulation is generally more difficult in fine-textured, stratified and slowly permeable soils.

Automated solid-set and centre-pivot sprinklers systems are conducive to good control and uniform distribution of applied water; in principle, trickle irrigation is even better. But gravity systems, if designed and operated properly, can also achieve good uniformity. Precision land grading and use of smaller water applications should be used to facilitate the achievement of high uniformity of areal water distribution over the field and infiltration, respectively. Closed conduits, rather than open waterways should be used for water distribution laterals if possible; they have the advantage of more effective off-on control, in addition to capturing gravitational energy for use in pressurizing delivery systems or controls which offer better potential for achieving high irrigation efficiencies.

The most advanced centre pivot irrigation system now used by some farmers in the USA is called the LEPA system - Low Energy Precision Application. In this system the sprinkler and spray nozzles used on the centre pivot systems are replaced with drop-down hoses and low pressure emitters that operate at only 0.3 $kg/cm^2$ and are placed as close as 20-45 cm above the ground. Experience has shown that these systems can reduce evaporation and wind-drift losses to less than 5 percent of the emitted water.

The new LEPA technology became commercially available in 1986 and since then has been adopted by an estimated 1000 farmers. The advantage of LEPA with regard to saline water irrigation is that it can irrigate crops with the right amount of water, avoiding excess and runoff, and minimize foliar damage which is common with saline water irrigation. However, the technique is new, costly and needs to be further developed to reduce costs and make the system simpler for adoption by a wider group of farmers.

In furrow-irrigated areas, furrow length should be reduced in order to improve intake distribution and to reduce tail water runoff. Worstell's (1979) multi-set system is useful for such purposes. Surge irrigation techniques can sometimes be used to improve irrigation uniformity in graded furrows (Bishop *et al.* 1981). For tree crops, a low-head bubbler system can be used to provide excellent control and to minimize the pressure requirements and expensive filtration systems (Rawlins 1977). Drip systems, of course, are increasingly being used for permanent crops and high-value annual crops and are well suited for use with saline irrigation waters. All opportunities to modify existing irrigation systems to increase their effectiveness of water and salinity control should be sought and implemented. Irrigation management technology for salinity control is the subject of reviews by van Schilfgaarde (1976); van Schilfgaarde and Rawlins (1980) and Kruse *et al.* (1990).

A frequent constraint in improving on-farm water use is the lack of knowledge of just when an irrigation is needed and of how much capacity for storage is available in the rootzone. Ways to detect the onset of plant stress and to determine the amount of depleted soil water are prerequisites to supplying water on demand and in the amount needed. Prevalent methods of scheduling irrigation usually do not, but should, incorporate salinity effects on soil-water availability (Rhoades *et al.* 1981). When irrigating with saline waters, the osmotic component of the soil water potential of the rootzone must be considered in scheduling decisions.

Ideally, irrigation management should have the available soil water near the upper limit during germination and emergence but depleted by about 50 percent, or more, at harvest and should maintain available water within the major rootzone during the early vegetative, flowering and yield formation growth stages at a level which produces no deleterious plant water stress through successive, properly-timed irrigations (Doorenbos and Kassam; FAO 1979). Under saline conditions, some "extra" water must be given for leaching - a minimum commensurate with salt tolerance of the crop being grown, if rainfall is inadequate in this regard, as discussed previously. Some method of assessing the water availability to the crop with sufficient lead time to provide for a water application before significant stress occurs should be used for irrigation scheduling purposes. In addition, the amounts of water needed for replenishment of the depleted soil moisture from the rootzone and for leaching must be determined.

Prevalent methods used to determine the onset of stress include both direct and indirect measurements. Leaf water potential can be measured with a pressure "bomb" and used to determine the onset of stress; however, the method does not give information with which to predict when the stress will occur much in advance of its occurrence, nor does it provide a measure of the amount of water to apply. Infrared thermometry can also be used to measure plant water stress indirectly which results in the partial closure of leaf stomates and in reduced transpiration rates, causing leaf temperature to rise abnormally above ambient air temperature. This temperature difference can be interpreted in terms of a crop water stress index with which irrigation-need can be assessed. It suffers the same limitation as the leaf water potential method.

Various scheduling methods can be used which are based on sensing depletion of soil water *per se* or soil water potential (matric, osmotic or total), or some associated soil or water property, and knowledge of the critical level (the set-point value). Such levels can be ascertained from salt tolerance data (see Tables 10-13) by converting threshold $EC_e$ values to osmotic potentials and assuming equivalent crop yield loss (also ET loss) would result from total water potential (i.e. assuming the effects of matric and osmotic potentials are equivalent and additive). Matric potential should be measured by any suitable means. Osmotic potential should be determined by one of the methods of salinity measurement described in Rhoades (1990b). Daily potential evapotranspiration can be calculated from measurements of air temperature, humidity, solar radiation and wind or of pan evaporation. The actual evapotranspiration ($ET_a$) can then be estimated from empirically determined crop coefficients as described by Doorenbos and Kassam (FAO 1979). The summation of these daily $ET_a$ values can then be used to estimate accumulative soil water depletion and total water potential. A plot of depletion or water potential versus time is then used to project the need for irrigation. This basic approach can be used based regardless of whether direct measurements of soil water content, or a related parameter, using neutron meters, resistance blocks, time-domain reflectometric (TDR) sensors, four-electrode sensors, or various soil matric potential sensors, etc., are used or estimated from ET methods. All of the methods suffer the limitation of needing to know the critical set-point value for irrigation, which varies with crop type, rooting characteristics, stage of plant growth, soil properties and climatic stress, etc. An estimate of this value can be obtained as described above or by the method of Doorenbos and Kassam (FAO 1979).

For saline water, irrigations should be scheduled before the total soil water potential (matric plus osmotic) drops below the level (as estimated above) which permits the crop to extract sufficient water to sustain its physiologic processes without loss in yield. Since, typically, the crop's root system normally extracts progressively less water with increasing soil depth (because rooting density decreases with depth and salt concentration increases with depth, as discussed earlier), the frequency of irrigations should be determined by the level of total soil water potential in the upper half of the rootzone where the rate of water depletion is greatest. Besides the extent of soil water depletion by ET, determination of the amount of water to apply should also be based on stage of plant development, the salt tolerance of the crop at this stage and the status of the soil water salinity at deeper depths in the rootzone. In early stages of plant development it is often desirable to irrigate just sufficiently to bring the soil to "field capacity" to the depth of present-rooting or just beyond. Eventually, however, excess water must be applied to leach salts accumulated in the upper profile to deeper depth in order to provide the growing plant access to more "usable" soil water in accordance with its expanding needs. Thus, the amount of irrigation water required is dictated by the plant's need for water, the volume of soil reservoir in need of replenishment and the level of soil salinity in the lower rootzone. Benefits of different amounts of saline irrigation water should be determined by evaluating their effects on relative crop yield using the water production function model.

For more discussion on irrigation management for salinity control, see the reviews of van Schilfgaarde (1976), van Schilfgaarde and Rawlins (1980), Hoffman **et al.** (1990), Shalhevet (1984) and Kruse *et al.* (1990).

## Monitoring Soil Water and Salinity and Assessing Adequacy of Leaching and Drainage

"Feedback" information on the status of salt and water within the crop rootzone and the extent of leaching being achieved should be obtained periodically to identify developing problem areas, to evaluate the appropriateness of model predictions and as a guide to r the effectiveness of the irrigation system and management strategies being used. Soil water content (or matric potential), salinity (and hence osmotic potential) and leaching fraction can, in theory, all be determined from measurements of soil electrical conductivity, $EC_a$, since $EC_a$ is a measure of both soil water content and soil water salinity. Soil salinity in irrigated agriculture is normally low at shallow soil depths and increases through the rootzone. Thus measurements of $EC_a$ in shallow depths of the soil profile made over an irrigation cycle are relatively more indicative of changing soil water content (permitting estimation of matric potential), while measurements of $EC_a$ in deeper depths of the profile, where less water uptake occurs, are relatively more indicative of salinity. Thus, in principle, depletion of soil water to a set-point level, depth of water penetration from an irrigation or rainfall event and leaching fraction can all be determined from ECa measurements made within the rootzone over time (Rhoades 1980; Rhoades *et al.* 1981). However, separate measurements of soil water content and soil water salinity, from which the total water potential can be estimated (matric plus osmotic), are more ideally suited for these needs. The use of time domain reflectometric (TDR) sensors offer potential in this regard (Dalton and Poss 1990).

Proper operation of a viable, permanent irrigated agriculture, which also uses water efficiently, requires periodic information on soil salinity, especially with use of saline waters. Only with this information can the effectiveness of irrigation project operation be assessed with respect to the adequacy of leaching and drainage, salt balance and water use efficiency. Monitoring programs should be implemented to evaluate the appropriateness of model predictions, the effectiveness of control programs, and to assess the adequacy of the irrigation and drainage systems on a project-wide basis. Frequently used methods based on "salt-balance" calculations are inadequate in this regard, for reasons given elsewhere (Kaddah and Rhoades 1976).

The direct inventorying and monitoring of soil salinity which are appropriate and needed in this regard are complicated by salinity's spatial variability, since numerous samples are needed to characterize an area. Monitoring is also complicated by salinity's dynamic nature, due to the influence of changing weather patterns, management practices, water table depth, etc. When the need for repeated measurements is multiplied by the extensive requirements of a single sampling period, the expenditures of time and effort with conventional soil sampling procedures increase proportionately. Hence, simple, practical methods for measuring or predicting field salinity are needed. Procedures for delineating representative areas within irrigation projects, where periodic measurements can be made for monitoring, are also needed, as are procedures for rapidly producing soil salinity maps. For these reasons new instruments for measuring soil electrical conductivity should be used and coupled with mobile transport vehicles, remotely sensed imagery and computer mapping techniques into an integrated system for inventorying and monitoring soil salinity. These procedures should also be integrated with solute-transport models to develop a geographic information system for salinity assessment and management needs. A network of representative soil salinity monitoring stations should be established in irrigation projects, especially those projects where saline waters are used for irrigation. For a discussion of mobilized, automated, and instrumental methods of salinity inventorying and monitoring see Rhoades (1990b; 1991).

For more discussion of the principles and practices of irrigation soil salinity control see the reviews of Rhoades 1987a; Hoffman *et al.* 1990; Rhoades and Loveday 1990; and Kruse *et al.* 1990.

## MANAGEMENT FOR ENVIRONMENTAL PROTECTION

### Practices to Control Salinity in Water Resources

As discussed previously, irrigated agriculture is a major contributor to the salinity of many surface- and groundwaters. The agricultural community has a responsibility to protect the quality of these waters. It must also maintain a viable, permanent irrigated agriculture. Irrigated agriculture cannot be sustained without adequate leaching and drainage to prevent excessive salinization of the soil, yet these processes are the very ones that contribute to the salt loading of surface and groundwaters. But surface and groundwater salinity could be reduced if salt loading contributions from the irrigation processes were minimized or eliminated. The protection of water resources against excessive salination, while sustaining agricultural production through irrigation, requires the implementation of comprehensive land and water use policies that incorporate the natural processes involved in the soil-plant-water and associated geohydrological systems.

Strategies to consider in coping with increasing salinity in receiving water systems resulting from irrigation include:

- eliminating irrigation of certain polluting lands;
- intercepting point sources of drainage return flow and diverting them to other uses;
- reducing the amount of water lost in seepage and deep percolation;
- isolating saline drainage water from good quality water supplies.

Only the last two strategies are discussed herein, primarily the last one.

#### *Minimizing Deep Percolation and Intercepting Drainage*

As discussed earlier, minimizing leaching always reduces the salt discharged from the rootzone. Additionally, deeply percolating water often displaces saline groundwater of higher salinity or dissolves additional salt from the subsoil. Reducing deep percolation will generally reduce the salt load returned to the river as well as reduce water loss. The "minimized leaching" concept of irrigation which reduces deep percolation should be adopted and implemented to reduce salinization of water resources associated with irrigation projects, especially in projects underlain by salt-laden sediments (van Schilfgaarde *et al.* 1974; Rhoades and Suarez 1977). In addition, saline drainage water should be intercepted. Intercepted saline drainage water can be desalted and reused, disposed of by pond evaporation or by injection into some isolated deep aquifer, or it can be used as a water supply where use of saline water is appropriate. Desalination of agricultural drainage waters for improving water quality is not generally economically feasible even though it is to be implemented for the return flow of the Wellton-Mohawk irrigation project of Arizona, USA. The high costs of the pretreatment, maintenance, and power are deterrents. Only in extreme cases, or for political rather than technical reasons, is desalination advocated (van Schilfgaarde 1979; 1982).

#### *Isolating and Reusing Drainage Water for Irrigation*

While there is an excellent opportunity to reduce the salt load contributed by drainage water through better irrigation management, especially through reductions in seepage and deep percolation, there are practical constraints which limit such reductions. But the ultimate goal should be to maximize the utilization of the irrigation water supply in a single application with minimum drainage. To the extent that the drainage water still has value for transpirational use by a crop of higher salt tolerance, it should be used again for irrigation.

Drainage waters are often returned by diffuse flow or intentional direct discharge to the watercourse and automatically "reused." Dilution of return flows is often advocated for controlling water salinity. This concept has serious limitations when one considers its overall effect on the volume of usable water, and it should not be advocated as a general method of salinity control.

The preferred strategy to control the salinity of water resources associated with irrigated lands is to intercept drainage waters before they are returned to the river and to use them for irrigation by substituting them for the low-salinity water normally used for irrigation at certain periods during the irrigation season of certain crops in the rotation. When the drainage water quality is such that its potential for reuse is exhausted then this drainage should be discharged to some appropriate outlet. This strategy will conserve water, sustain crop production and minimize the salt loading of rivers that occurs by irrigation return flow (Rhoades 1984a, b, c). It will also reduce the amount of water that needs to be diverted for irrigation. This strategy is discussed in more detail in the next section.

## Integrated Strategy to Facilitate the Use of Saline Waters for Irrigation, to Minimize Drainage Disposal Problems and to Maximize the Beneficial Use of Multiple Water Sources

As indicated in the preceding section, the ultimate goal of irrigation management should be to minimize the amount of water extracted from a good-quality water supply and to maximize the utilization of the extracted portion during irrigation use, so that as much of it as possible is consumed in transpiration (hence producing biomass) and as little as possible is wasted and discharged as drainage. Towards this goal, to the extent that the drainage water from a field or project still has value for transpirational use by a crop of higher salt tolerance, it should be used again for irrigation before ultimate disposal.

It is the intent of this section to describe an integrated strategy of management that will simultaneously facilitate the successful use of saline waters for irrigation, minimize the harmful off-site effects of drainage discharge on the pollution of water resources and maximize the beneficial use of the total water supply available in typical irrigated lands and projects. This strategy illustrates how the information and principles given in the preceding sections of these guidelines can be integrated towards the goals of sustaining irrigated agriculture and protecting soil and water resources.

To the extent practical, water diverted and applied for irrigation should be minimized using the principles and methods previously discussed. Unavoidable excessive, usable resulting drainage water should be intercepted and isolated from good-quality water supplies and used within dedicated parts of the project as a substitute for part of the freshwater given to the crops. The "dual rotation, cyclic" management strategy of Rhoades (1984a, b, c) can be used to enhance the feasibility of reusing such saline drainage waters for irrigation. In this system, sensitive crops (such as lettuce, alfalfa, etc.) in the rotation are irrigated with "low salinity" water (usually the developed water supply of the irrigation project), and salt-tolerant crops (such as cotton, sugarbeets, wheat, etc.) are irrigated with saline drainage water or the shallow groundwater created by over-irrigation in the project. For the salt-tolerant crops, the switch to saline water is usually made after seedling establishment; preplant irrigations and initial irrigations being made with low-salinity irrigation water. The secondary drainage resulting from such re-use should also be isolated and used successively for crops (including halophytes and tolerant trees) of increasingly greater salt tolerance. The ultimate unusable drainage water should be disposed of to some appropriate outlet or treatment facility.

The feasibility of this "dual-rotation, cyclic" strategy is supported by the following:

- The maximum possible soil salinity in the rootzone resulting from continuous use of saline water does not occur when this water is used only for a fraction of the time.

- Alleviation of salt build-up resulting from irrigation of salt-tolerant crops with the saline water occurs later when a salt-sensitive crop(s) is irrigated with the low-salinity water supply, or during off season periods of high rainfall.

- Proper preplant irrigation and careful irrigation management undertaken during germination and seedling establishment are made using the low-salinity water supply to leach salts accumulated from saline irrigations out of the seed-area and from shallow soil depths.

- Data obtained in modelling studies and in field experiments support the credibility and feasibility of this "cyclic" reuse strategy (Rhoades 1977; 1989; Rhoades *et al.* 1989a, b, and c; Minhas *et al.* 1989; 1990a and b).

Results of an experiment to test the feasibility of the cyclic, "dual-rotation" reuse strategy are reviewed to clarify and illustrate the concept and to demonstrate its credibility. The strategy was tested in a 20 ha field experiment on a commercial farm in the Imperial Valley of California (Rhoades *et al.* 1989a, b, c). Two cropping patterns were tested. One was a two-year, successive-crop rotation of wheat, sugarbeets and cantaloupe melons. In this rotation, Colorado River water (900 mg/l TDS) was used for the preplant and early vegetative growth stage irrigations of wheat and sugarbeets and for all irrigations of the melons. The remaining irrigations were with drainage water of 3500 mg/l TDS (Alamo River water). The other cropping pattern tested was a four-year block rotation consisting of two consecutive years of cotton (a salt-tolerant crop) followed by wheat (a crop of intermediate salt-tolerance) and then by two years of continuous alfalfa (a relatively salt-sensitive crop). Drainage water was used for the irrigation of cotton after seedling establishment; beginning with the wheat crop, only Colorado River water was used. From Watsuit calculations, it was hypothesized that the crops irrigated with the drainage water would yield fully when established with Colorado River water and from other calculations that sufficient desalination of the soil would occur when irrigating with Colorado River water to achieve a good plant stand and to keep the soil from becoming excessively saline over the long-run.

The yields of the crops grown in the successive and block rotations are given in Tables 40 and 41, respectively. No significant losses in the yields of the wheat and sugarbeet crops occurred in either cycle of the successive crop rotation from substituting drainage water (even in the greater amount; 65-75 percent; treatment cA) for Colorado River water for the irrigation of these crops after seedling establishment. The mean yield of cantaloupe seed obtained in the cA plots was about 10 percent lower than the control, but the difference was not statistically significant. The yields of the fresh-market melons (numbers of cartons of cantaloupes obtained by commercial harvest operations) in 1985 was higher in the Ca and cA

TABLE 40
**Yields of crops in successive rotation** (after Rhoades *et al.* 1989a)

| Treatment[1] | Crop/year | | | | | |
|---|---|---|---|---|---|---|
| | wheat/ 1982[2] | sugarbeets/ 1983[3] | cantaloupes/ 1983[4] | wheat/ 1984[2] | sugarbeets/ 1985[3] | cantaloupes/ 1985[5] |
| C | 3.60 (0.06)[6] | 4.3 (0.1) | 392 (12) | 3.51 (0.09) | 4.1 (0.1) | 115 (5) |
| Ca | 3.60 (0.08) | 4.3 (0.2) | 384 (10) | 3.46 (0.10) | 4.1 (0.1) | 142 (8) |
| cA | 3.71 (0.06) | 4.1 (0.1) | 355 (14) | 3.55 (0.09) | 3.9 (0.1) | 139 (12) |

1 C = Colorado River water used solely for irrigation; Alamo River water used in relatively smaller (Ca) and larger (cA) amounts, after seedling establishment with Colorado River water for wheat and sugarbeets. Cantaloupes only irrigated with Colorado River water.
2 Tons of grain per acre.
3 Tons of sugar per acre.
4 Lbs of seed per acre.
5 Commercial yield in number of cartons per plot; plot size = 750 x 38 feet = 0.6543 acres.
6 Value within ( ) is standard error of mean; six replicates.

TABLE 41
**Yields of crops in block rotation** (after Rhoades *et al.* 1989a)

| Treatment[1] | Crop/year | | | |
|---|---|---|---|---|
| | cotton/1982[2] | cotton/1983[2] | wheat/1984[3] | alfalfa/1985[4] |
| C | 2.62(.07)[5] | 2.06(.10) | 3.43(.06) | 7.8(0.4) |
| cA | 2.65(.06) | 2.00(.09) | 3.43(.06) | 7.0(0.5) |
| A | 2.76(.04) | 1.32(.05) | 3.41(.05) | 7.4(0.3) |

1 C = Colorado River water used solely for irrigation; A = Alamo River water used solely for irrigation; cA = Alamo River water used for irrigation after seedling establishment with Colorado River water for cotton. Wheat and alfalfa irrigated only with Colorado River water.
2 Commercial yield of lint, bales per acre.
3 Tons of grain per acre.
4 Tons of dry hay per acre.
5 Value within ( ) is standard error of mean; six replicates.

treatments than in the C treatment, but they were not significantly different (see Table 40). Hence, no significant yield loss was observed from growing cantaloupes using Colorado River for irrigation in the land previously salinized from the irrigation of wheat and sugarbeets using drainage water.

In the block rotation, there was no loss in lint yield in the first cotton crop (1982) from use of saline drainage water for irrigation, even when it was used for all irrigations, including the preplant and seedling establishment periods (treatment A). There was no significant loss in lint yield in the second cotton crop (1983) grown in the block rotation from use of drainage water for the irrigations given following seedling establishment which was accomplished using Colorado River (the recommended strategy treatment, cA). But there was a significant and substantial loss of lint yield, as expected, where the drainage water was used solely for irrigation (the "extreme - control" treatment, A). This loss of yield was caused primarily by a loss of stand that occurred this second year due to excess salinity in the seedbed during the establishment period. No loss in yield of the wheat grain or alfalfa hay crops occurred in the block rotation associated with the previous use of drainage water to grow cotton on these lands when they were subsequently grown with use of Colorado River water for irrigation. The qualities of all of these crops were never inferior, and often were superior, when grown using the drainage water for irrigation or on the land where it had previously been used. These quality data are given elsewhere (Rhoades *et al.* 1989a, b).

The average amounts of water applied to each crop and over the entire four-year period are given in Tables 42 and 43 for the successive and block rotations, respectively. These data include all water applied, including that used for preplant irrigations and land preparation purposes. These data along with those in Tables 40 and 41 show that substantial amounts of drainage water were substituted for Colorado River water in the irrigation of these crops without yield loss.

The estimated amounts of water consumed by the crops through evapotranspiration and lost as deep percolation are given in Table 44 by individual crop and by succession of crops for both rotations. It was assumed that consumptive use was the same in all treatments, since no substantial losses of yield resulted in any treatment. These data show that the saline drainage water was successfully used for irrigation without resorting to high leaching. Data on levels of soil salinity and sodicity in the seedbeds and rootzones are given in Rhoades *et al.* (1989b). Their levels were kept within acceptable limits for seedling establishment and the subsequent growth of the individual crops grown in the rotation when the recommended strategy was employed. These results along with the high crop yields and qualities obtained in this test under actual farming conditions support the credibility of the recommended cyclic, dual-rotation (crop and water) strategy to facilitate the use of saline waters for irrigation.

In this cyclic strategy, steady-state salinity conditions in the soil profile are never reached, since the irrigation water quality changes with crop type in the rotation and with time in the irrigation season. Consequently, a flexible cropping pattern which includes salt-sensitive crops can be achieved. The intermittent leaching which occurs using this strategy is more effective in leaching salts than is continuous leaching (i.e. imposing a leaching fraction with each irrigation) for the reasons given earlier. Another advantage of the strategy is that a facility for blending waters of different qualities is not required.

In order to plan and implement a successful practice involving the use of the cyclic, dual-rotation strategy for irrigating with saline waters, various other considerations must be addressed. The intention here is not to provide a step-by-step process that must be followed nor a rigid set of criteria to address these considerations, since most management decisions are subjective and case specific, but to discuss some of the factors that should be considered and to provide some rough guidelines for selecting appropriate management practices.

Perhaps the most important management decision to make before implementing a reuse practice is crop selection. Crop tolerances of crops to salinity and to specific elements are given in Tables 13-21. A list of other criteria that should be considered in the selection of crops for a reuse practice is given in Table 45. In most cases, it is recommended that crops of high tolerance to salinity be selected when saline drainage water is to be used for irrigation. However, crops of intermediate tolerance (e.g. alfalfa, melons, tomatoes and wheat) may also be used in some cases, especially if the crop quality is sufficiently benefitted. For example, drainage water (EC 4 - 8 dS/m) significantly increased the protein content of wheat and alfalfa (Rhoades *et al.* 1989a), soluble solids in melons and tomatoes (Grattan *et al.* 1987), total digestible nutrients in alfalfa (Rhoades *et al.* 1989a), and

TABLE 42
**Amounts of Colorado and Alamo river waters used for irrigation in successive crop rotation (mm)** (after Rhoades *et al.* 1989b)[1]

| Treatment[2] | 1982 wheat | | | | 1983 sugarbeets | | | | 1983 cantaloupes | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Colorado River | Alamo River | Total | % Alamo | Colorado River | Alamo River | Total | % Alamo | Colorado River | Alamo River | Total | % Alamo |
| C | 548(3)[3] | 0 | 548(3) | 0 | 1268(5) | 0 | 1268(5) | 0 | 626(7) | 0 | 626(7) | 0 |
| Ca | 417(5) | 129(1) | 545(4) | 24 | 712(1) | 536(2) | 1249(2) | 43 | 623(2) | 0 | 623(2) | 0 |
| cA | 131(1) | 425(4) | 556(4) | 76 | 448(3) | 800(3) | 1248(4) | 64 | 628(3) | 0 | 628(3) | 0 |
| | 1984 wheat | | | | 1985 sugarbeets | | | | 1985 cantaloupes | | | |
| | Colorado River | Alamo River | Total | % Alamo | Colorado River | Alamo River | Total | % Alamo | | | | |
| C | 823(4) | 0 | 823(4) | 0 | 1400(4) | 0 | 1400(4) | 0 | 360(6) | 0 | 360(6) | 0 |
| Ca | 431(2) | 396(2) | 827(2) | 48 | 711(3) | 663(3) | 1374(5) | 48 | 354(4) | 0 | 354(4) | 0 |
| cA | 307(2) | 526(2) | 833(3) | 63 | 491(2) | 873(4) | 1364(4) | 64 | 346(4) | 0 | 346(4) | 0 |
| | Complete rotation | | | | | | | | | | | |
| | Colorado River | Alamo River | Total | % Alamo | | | | | | | | |
| C | 5025(12) | 0 | 5025(12) | 0 | | | | | | | | |
| Ca | 3248(9) | 1724(5) | 4971(11) | 35 | | | | | | | | |
| cA | 2351(7) | 2624(3) | 4975(10) | 53 | | | | | | | | |

1 Includes preplant water applications.
2 C = Colorado River water used solely for irrigation; Alamo River water used for irrigation in relatively smaller (Ca) and larger (cA) amounts after seedling establishment with Colorado River water.
3 Number within ( ) is standard error of mean.

TABLE 43
**Amounts of Colorado and Alamo river waters used for irrigation in the block rotation (mm)** (after Rhoades *et al.* 1989b)

| Treatment[2] | 1982 cotton | | | | 1983 cotton | | | | 1984 wheat | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Colorado River | Alamo River | Total | % Alamo | Colorado River | Alamo River | Total | % Alamo | Colorado River | Alamo River | Total | % Alamo |
| C | 1306(19)[3] | 0 | 1306(19) | 0 | 1177(6) | 0 | 1177(6) | 0 | 823(8) | 0 | 823(8) | 0 |
| cA | 515(12) | 774(30) | 1289(42) | 60 | 617(4) | 545(3) | 1162(6) | 47 | 798(2) | 0 | 798(2) | 0 |
| A | 0 | 1187(25) | 1187(25) | 100 | 0 | 1149(7) | 1149(7) | 100 | 795(5) | 0 | 795(5) | 0 |

| | alfalfa | | | | complete rotation | | | |
|---|---|---|---|---|---|---|---|---|
| | Colorado River | Alamo River | Total | % Alamo | Colorado River | Alamo River | Total | % Alamo |
| C | 2048(6) | 0 | 2048(6) | 0 | 5372(8) | 0 | 5372(8) | 0 |
| cA | 2058(7) | 0 | 2058(7) | 0 | 3995(18) | 1132(34) | 5327(50) | 25 |
| A | 2029(16) | 0 | 2029(16) | 0 | 2824(17) | 2336(30) | 5160(42) | 45 |

1 Includes preplant water applications.
2 C = Colorado River water used solely for irrigation; Alamo River water used for irrigation in relatively smaller (Ca) and larger (cA) amounts after seedling establishment with Colorado River water.
3 Number within ( ) is standard error of mean.

TABLE 44
**Estimated evapotranspiration and deep percolation (inches)** (after Rhoades *et al.* 1989b)

| Crop | $V_{et}$[1] | $V_{iw}$[2] | $V_{dw}$[3] | LF[4] | Accumulated[5] | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | $V_{et}$ | $V_{iw}$ | $V_{dw}$ | LF |
| Successive crop rotation | | | | | | | | |
| 1982 wheat | 25.8 | 21.9 | -3.9 | -0.18 | 25.8 | 21.9 | -3.9 | -0.18 |
| 1983 s.beet | 40.5 | 49.1 | 8.6 | 0.18 | 66.3 | 71.0 | 4.7 | 0.07 |
| 1983 melons | 16.8 | 24.7 | 7.9 | 0.32 | 83.1 | 95.7 | 12.6 | 0.13 |
| 1984 wheat | 27.1 | 32.8 | 5.7 | 0.17 | 110.2 | 128.5 | 18.3 | 0.14 |
| 1985 s.beet | 42.3 | 53.7 | 11.4 | 0.21 | 152.5 | 182.2 | 29.7 | 0.16 |
| 1985 melons | 16.8 | 13.6 | -3.2 | -0.24 | 169.3 | 195.8 | 26.5 | 0.14 |
| Block rotation | | | | | | | | |
| 1982 cotton | 38.9 | 50.7 | 11.8 | 0.23 | 38.9 | 50.7 | 11.9 | 0.23 |
| 1983 cotton | 40.7 | 45.7 | 5.0 | 0.11 | 79.6 | 96.5 | 16.9 | 0.18 |
| 1984 wheat | 27.1 | 31.4 | 4.3 | 0.14 | 106.7 | 127.9 | 21.3 | 0.17 |
| 1985 alfalfa | 81.2 | 81.0 | -0.2 | -0.00 | 187.8 | 208.9 | 21.1 | 0.10 |

1 Evapotranspiration estimated from pan evaporation and crop factors at Brawley, California.
2 Total amount of water applied for irrigation.
3 Estimate of deep percolation drainage water i.e. $V_{iw}$ - $V_{et}$.
4 Estimate of leaching fraction, i.e. $V_{dw}/V_{iw}$.
5 Accumulated over entire experimental period.

TABLE 45
**Criteria to be considered for selecting crops for a reuse practice** (after Grattan and Rhoades 1990)

| Selection criteria | | Desirable | Undesirable |
|---|---|---|---|
| 1. | Economic value/ marketability | high marketability | low, unmarketable |
| 2. | Crop salt tolerance | tolerant | sensitive |
| 3. | Crop boron/chloride tolerance | tolerant | sensitive |
| 4. | Crop potential to accumulate toxic constituent | toxic element excluder | toxic element accumulation |
| 5. | Crop quality | unaffected or improved by saline water | adversely affected by saline water |
| 6. | Crop rotation consideration | compatible | incompatible |
| 7. | Management/ environmental conditions requirements | Easy management, able to grow under diverse conditions | requires intensive management and can only be grown under very specific conditions |

improved colour and netting of cantaloupe (Rhoades *et al.* 1989a), and improved peelability in processing tomato (Grattan and Rhoades 1990). While improved plant quality should not be the major factor in adopting a reuse practice it may be an important factor in crop selection. Use of saline water to irrigate crops of intermediate tolerance to salinity is feasible, of course, only after seedlings have been established by good quality water.

Economics is also an important selection consideration, since it would be senseless to grow a high yielding crop without a marketable product and the potential for a positive cash flow. In the San Joaquin Valley in California, there is negative correlation between crop tolerance to salinity and economic value (Grattan and Rhoades 1990). It is unfortunate that there are not many crops that are both tolerant to salinity and have a high economic value. Asparagus is tolerant to salinity and has a high economic value, but harvesting is labour-intensive and costly.

The cyclic, "dual-rotation" reuse strategy described above presupposes the availability of two water sources; the saline water to be utilized and the other a water of low salinity. Such reuse requires that the saline water be readily accessible for irrigation. Possible sources can be the drainage waters that are being discharged in pipes or canals from the irrigation project or that present in the underlying shallow groundwater system. Rainfall may also be the source of good-quality water, if it occurs at required times during the year to meet crop needs periodically and to leach excessive accumulations of soluble salts from the rootzone.

There are many different situations where the use of saline water for irrigation in the recommended strategy could be practical. One situation is where high quality water is available during the early growing season but is either too costly or too limited in supply to meet the entire seasons requirements. This situation is common in parts of India and Pakistan, for example. Where high-quality water costs are prohibitive, crops of moderate to high salt tolerance could be irrigated with saline drainage or groundwater, especially at later growth stages with economical advantage, even if this practice resulted in some reduction in yield relative to that obtainable with a full supply of fresh water. Use of saline water for irrigation reduces the amount of high-quality water required to grow crops and hence expands the water-resource base for crop production.

Another situation conducive for such reuse is one where drainage water disposal, or a means of lowering an excessively shallow water table, is impractical due to physical, environmental, social or political factors. Reuse of the drainage water for irrigation in this situation decreases the volume of drainage water requiring disposal or treatment, and the associated costs. Furthermore, a reduction in the drainage volume also reduces the salt loading of the receiving water. Many growers in the San Joaquin Valley of California are presently undertaking reuse of drainage water, at least as a temporary solution, in order to reduce drainage volume and to meet recently imposed discharge restrictions related to protection of the quality and ecology of receiving water systems.

A difficulty in adopting the cyclic, "dual-rotation" strategy may exist on small farms where the drainage water produced on-site is too little or does not coincide with peak crop-water demand. In the San Joaquin Valley in California, farms are often sufficiently large but peak drain water flow occurs from January to June when most crops would require high quality water. Sole use of drainage water later in the season may not be feasible if the flow rate needed for irrigation exceeds the flow rate from the drains. To avoid this limitation, surface storage reservoirs can be constructed to store the drainage water until its use is required. An option is to plug the subsurface drains and allow the soil to act as the reservoir. The latter option would not take land out of production for water storage purposes. However, regardless of where the drainage water is stored, a drainage water collection and irrigation system should be designed and operated with "reuse" in mind in order to implement this strategy most efficiently.

One method of collecting sufficient quantities of drainage water is to install a network of interceptor drains in areas with shallow water tables. A submersible pump could be placed in collector sumps as a means to access the drainage water. The size of the area that can be irrigated using such "drainage water" will vary, of course, depending on the capacity of the drainage system. To surface irrigate effectively, at least 10 litres/min/ha is required. Another way to collect drainage water is to install a network of shallow wells in strategic shallow water table areas. The wells can be connected to a common drainage manifold to facilitate collection and distribution. Consultation with irrigation and drainage engineers is advised before installing any drainage water collection system for irrigation use.

The long-term feasibility of using drainage water for irrigation in order to reduce drainage volume would likely be increased if implemented on a project or regional scale such as shown in Figure 17, rather than on a farm scale. Regional management permits reuse in dedicated areas so as to avoid the successive increase in concentration of the drainage water that would occur if the reuse process were to operate on the same water supply and same land area (i.e. in a closed loop). With regional management, certain areas in the region can be dedicated to reuse while other areas such as upslope areas, are irrigated solely with high quality water as usual. The second-generation drainage water from the primary reuse area is discharged to other dedicated reuse areas where even more salt-tolerant crops are grown, or to regional evaporation ponds or to treatment plants. Ideally, regional coordination and cost-sharing among growers should be undertaken in such a regional reuse system.

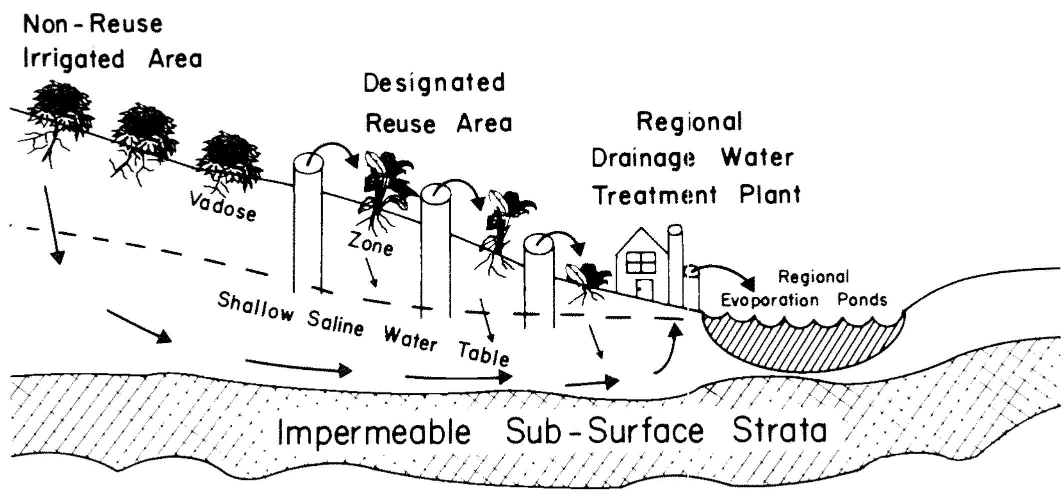
A novel means of "treating" saline waste waters before their ultimate disposal is to use them to irrigate specific crops that have the ability to accumulate large quantities of undesirable constituents (e.g. Se, Mo, $NO_3$, B, etc.) in the plants, in order to help reduce adverse ecological effects of disposal. The feasibility of biofiltration, the term used to describe this process, has been demonstrated by Cervinka *et al.* (1987), and Wu *et al.* (1987). They found that mustard, some grasses and certain native plant species found in California are effective in accumulating substantial amounts of Se in their shoots. This alternative "reuse" practice is most attractive where: (i) drainage disposal problems exist related to a potentially toxic trace constituent, (ii) a bioaccumulator with economic value exists, and (iii) other treatment processes are either unavailable or too expensive.

An alternative reuse strategy that is often advocated is to blend water supplies before or during irrigation (Shalhevet 1984; Meiri *et al.* 1986; Rains 1987; Rolston *et al.* 1988). Blending may be appropriate provided the drainage or shallow groundwater is not too saline *per se* for the crop to be grown. However, in many cases this approach is inappropriate for the reasons given in chapter 5.

If the blending strategy is adopted, there must be a controlled means of mixing the water supplies. Shalhevet (1984) and Meiri *et al.* (1986) described two blending processes (i) network dilution, and (ii) soil dilution. With network dilution, water supplies are blended in the irrigation conveyance system. With soil dilution, the soil acts as the medium for mixing water of different qualities. A network blending system must be designed and installed if the blending strategy is to be adopted. The theory and design of dilution control systems and their use in irrigation networks has been developed by Sinai *et al.* (1985; 1989).

The cyclic strategy is preferred over the blending strategy in that (i) more salt sensitive crops can be included in the rotation, (ii) a blending facility is not required, and (iii) there is less danger in losing "usable water" for the crop. However, the cyclic strategy will require larger quantities of drainage water during the irrigations where it is used (since the water is

FIGURE 17
Regional drainage water reuse plan




not blended) and thus a storage system may be required in order to supply sufficient water for an effective irrigation. In summary, the "cyclic" strategy has more potential and flexibility than does the "blending" strategy, although the latter strategy is easier to implement in some cases.

Another concern besides excessive salinity build-up as regards the long-term feasibility of using saline water for irrigation is that of soil permeability and tilth. As discussed in chapter 4, the likelihood of these problems increase as SAR increases and as electrical conductivity decreases. Therefore, adverse effects are most likely to occur during the periods of rainfall and irrigation using low-salinity water on soils previously irrigated with sodic, saline water. Such problems occurred at an experimental "reuse" site in California following pre-season rains and pre-irrigation with 0.3 dS/m canal water where sodic, saline water [9000 mg/l TDS; SAR = 30 $(mmol_c/l)^{1/2}$] had been used for irrigation for four consecutive years (Rolston *et al.* 1988). The consequence was impermeable, crusted soils and poor stand establishment. Whether such a problem will occur, or not, depends upon whether the EC of the high quality water is less than the threshold value, given the SAR of the saline water. Some combinations of the two waters are not permissible. The methods given in chapter 4 may be used to assess whether such a problem is likely to occur or not. This problem can often be controlled by the use of amendments and appropriate tillage practices as discussed.

Soil salinity under the cyclic strategy will fluctuate more, both spatially and temporally than in soils irrigated with conventional water supplies. Therefore, predicting plant response will be more difficult under these conditions. Hence, long-term effects on soil salination should be monitored using the techniques described earlier. Management must be adjusted to keep the average rootzone salinity levels within acceptable limits for the crop being grown, considering its stage of growth.

Many saline waters contain certain elements, such as boron and chloride, that can potentially accumulate in plants, especially woody, perennial ones, to levels that cause foliar injury and a subsequent reduction in their yield. In such cases, toxicity may produce more long-term detrimental effects than does salinity. Since boron is adsorbed by the soil it requires longer to build to toxic levels in the soil solution and it requires more leaching to remove its excessive accumulations than does salinity. Thus long-term accumulation in the soil of potential toxicants must be considered, since toxic effects may not become evident for years and may be more difficult to eliminate. Water containing excessive concentrations of B or Cl should not be used to irrigate perennial crops, since (i) these crops are generally more sensitive to specific-ion effects (ii) they represent a long-term investment, and (iii) they will have a long time opportunity to accumulate toxic levels. This same concern applies to growing perennial crops in the presence of a shallow groundwater that contains solutes potentially toxic to the plant.

Another consideration as regards use of saline water for irrigation is the potential of the plant to accumulate certain elements (such as Se, Mo, heavy metals) that are toxic to consumers of the crops (humans and animals). For example, in the San Joaquin Valley of California, drainage water in several locations contains unusually high levels of Se ($\geq$ 50 $\mu$g Se/l). Although Se is essential to humans and animals in small amounts, excessive amounts can cause Se toxicosis. In the San Joaquin Valley, melons and processing tomatoes irrigated with drainage water containing 250 to 350 $\mu$g Se/l accumulated elevated levels of Se in the fruit (250 to 750 $\mu$g/kg, dry wt.) that, while not an immediate health hazard, might become so to one whose diet was mostly restricted to such food (Grattan *et al.* 1987; Fan and Jackson 1987). Many forages and native plant species have the potential to accumulate excessive amounts of Se (Wu *et al.* 1987). Since grazing animals consume larger quantities of plant mass than do humans, they have a greater potential for being "poisoned" in this manner.

Since plants vary in their ability to absorb and translocate toxic elements, crops that accumulate large quantities of toxic elements in the edible animal organs should also be avoided when using saline waters containing such elements for irrigation. Fleming (1962) found that Se concentrations were higher in *Cruciferae* (cabbage, cress, radish, rape and turnips), *Liliacea* (onion), and *Leguminosae* (clover and peas) than in *Compositae* (artichoke and lettuce), *Gramineae* (barley, oats, rye grass, and wheat), and *Umbelilferae* (parsnip and carrots) when grown on seleniferous soils in Ireland. It is also important to understand how the toxic constituent is partitioned within the plant. In most annual fruit and vegetable crops selenium accumulates more in the leaves than in the fruit (Mikkelson *et al.* 1988), but exceptions exist. If the saline water in question contains high levels of a potentially toxic element, the user should obtain expert advice.

# References

Abu-Zeid M. 1988. Egypt's policies to use low-quality water for irrigation. Proc. Symp. Re-use of Low-quality Water for Irrigation. Water Research Centre, Cairo.

Adams W.M. and Hughes F.M.R. 1990. Irrigation development in desert environments. In: Techniques for Desert Reclamation. A.S. Goudie (ed.). John Wiley, New York. pp. 135-160.

Amer M.H. and Ridder N.A. 1983. Land drainage in Egypt. Drainage Research Institute, Water Research Center, Cairo. 376 pp.

Ayers R.S. and Westcot D.W. 1985. Water quality for agriculture. Irrigation and Drainage Paper 29, Rev. 1. FAO, Rome. 174 pp.

Beek K.J., Blokhuis N.A., Driessen P., Van Breeman N., Brinkman R. and Pons L.J. 1980. Problem soils: their reclamation and management. ILRI Pub. No. 27, Wageningen. pp. 47-72.

Bernstein L. 1974. Crop growth and salinity. In: Drainage for Agriculture. J. van Schilfgaarde (ed.). Agronomy 17:39-54.

Bernstein L. 1975. Effects of salinity and sodicity on plant growth. Ann. Rev. Phytopathology 13:295-312.

Bernstein L. and Fireman M. 1957. Laboratory studies on salt distribution in furrow-irrigated soil with special reference to the pre-emergence period. Soil Sci. 83:249-263.

Bernstein L. 1980. Salt tolerance of fruit crops. US Dept. Agr. Info. Bull. 292, 8 pp.

Bernstein L. and Francois L.E. 1973a. Comparison of drip, furrow, and sprinkler irrigation. Soil Sci. 115:73-86.

Bernstein L. and Francois L.E. 1973b. Leaching requirement studies: Sensitivity of alfalfa to salinity of irrigation and drainage waters. Soil Sci. Soc. Amer. Proc. 37:931-943.

Bernstein L. and Pearson G.A. 1956. Influence of exchangeable sodium on the yield and chemical composition of plants. I. Greenbeans, garden beets, clover, and alfalfa. Soil Sci. 82:247-258.

Bernstein L., Fireman M. and Reeve R.C. 1955. Control of salinity in the Imperial Valley, California. US Dept. Agric. ARS-41-4. 16 pp.

Bhatti H.M. 1986. Management of irrigation water qualities for crop production. Final Technical Report PL-480. USDA Grant FG-Pa-266/PK-ARS-76. 115 pp.

Bielorai H., Shalhavet J. and Levy Y. 1978. Grapefruit response to variable salinity in irrigation water and soil. Irrig. Sci. 1:61-70.

Bingham F.T., Peryea F.J. and Rhoades J.D. 1981. Boron tolerance character of wheat. Proc. Inter-American Salinity and Water Management Technology, 11-12 December 1980, Juarez, Mexico. pp. 208-216.

Bishop A.A., Walker W.R., Allen N.L. and Poole G.J. 1981. Furrow advance rates under surge flow systems. J. irrig. and Drainage Div., ASCE 107(IR3):257-264.

Biswas A.K. 1990. Conservation and management of water resources. In: Techniques for Desert Reclamation. A.S. Goudie (ed.). John Wiley, New York. pp. 251-265.

Bos R. 1991. Water quality, disease and human health. Paper presented at the Water Quality Conference, Bratislava.

Boumans J.H., van Hoorn J.W., Kruseman G.P. and Tenwar B.S. 1988. Water table control, reuse and disposal of drainage water in Haryana. Agric. Water Mgmt. 14:537-545.

Bower C.A., Ogata G. and Tucker J.M. 1969. Rootzone salt profiles and alfalfa growth as influenced by irrigation water quality. Agron. J. 61:783-785.

Bower C.A., Ogata G. and Tucker J.M. 1970. Growth of Sudan and tall fescue grasses as influenced by irrigation water salinity and leaching fraction. Agron. J. 62:793-794.

Bresler E. 1987. Application of a conceptual model to irrigation water requirement and salt tolerance of crops. Soil Sci. Soc. Am. J. 51:788-793.

Bresler E. and Hoffman G.J. 1986. Irrigation management for salinity control: Theories and tests. Soil Sci. Soc. Am. J. 50:1552-1560.

Bresler E. and Yaron D. 1972. Soil water regime in economic evaluation of salinity in irrigation. Water Resources Research 8:791-800.

CAST (Council for Agricultural Science Technology). 1988. Effective use of water in irrigated agriculture. Report No. 113, Ames, Iowa.

Cervinka V., Finch C., Beyer J., Menezens F. and Ramirez R. 1987. The agroforestry demonstration program in the San Joaquin Valley. Progress Report. California Dept. of Food and Agriculture, Agricultural Resources Branch, Sacramento, California.

Corwin D.L. and Waggoner B.L. 1990. TETRANS: Solute transport modeling software user's guide (Macintosh Version 1.4). US Salinity Laboratory Report No. 121. pp. 1-50.

Craig J.R. 1980. Saline waters: genesis and relationship to sediments and host rocks. In: Saline Water Proc. Symp. Groundwater Salinity, 46th Annual Meeting. R.B. Mattox (ed.). Amer. Assoc. Adv. Sci (AAAS), Las Vegas, Nevada.

Dalton F.N. and Poss J.A. 1990. Soil water content and salinity assessment for irrigation scheduling using time-domain reflectometry: principles and applications. Acta Horticulturae. (Submitted).

De-Malach Y., Pasternak D., Twersky M. and Borovic I. 1978. Irrigation of sugarbeet with brackish water. Itasadeh 59:418-424.

Dinar A. and D. Zilberman (eds.). 1991. The Economics and Management of Water and Drainage in Agriculture. Kluwer Academic Publishers, Norwell, Massachusetts. 946 pp.

Dinar A., Knapp K.C. and Rhoades J.D. 1986. Production functions for cotton with dated irrigation water quantities and qualities. Water Resources Res. 22:1519-1525.

Doorenbos J. and Kassam A.H. 1979. Yield response to water. Irrigation and Drainage Paper 33. FAO, Rome. 193 pp.

Dutt G.R., Pennington D.A. and Turner F. Jr. 1984. Irrigation as a solution to salinity problems of river basins. In: Salinity in Watercourses and Reservoirs. R.H. French (ed.). Ann Arbor Science, Michigan. pp. 465-472.

Dutt G.R., Schaffer M.J. and Moore W.J. 1972. Computer simulation model of dynamic bio-physicochemical processes in soils. Univ. Arizona Agric. Exp. Stn., Tech. Bull. 196.

Emerson W.W. 1984. Soil Structure in Saline and Sodic Soils. Springer Verlag, New York. pp. 65-76.

Erickson J.R. 1980. Using high salinity waters in the Southwest. Proc. 1980 Speciality Conference on Irrigation and Drainage, Today's Challenges. 23-25 July 1980, Boise, Idaho. ASCE, New York. pp. 198-204.

Fan A.M. and Jackson R.J. 1987. Health assessment of human dietary selenium intake from agricultural crops. A report of the UC Salinity/Drainage Task Force. Div. of Agric. and Natural Resources, Univ. California. 22 pp.

FAO. 1976. Prognosis of salinity and alkalinity. Soils Bulletin 31. Rome.

FAO. 1979. Yield response to water. J. Doorenbos and A.H. Kassam. Irrigation and Drainage Paper 33. Rome. 193 pp.

FAO. 1984. Guidelines for predicting crop water requirements. J. Doorenbos and W.O. Pruitt. Irrigation and Drainage Paper 24. Rome.

FAO. 1985. Water quality for agriculture. R.S. Ayers and D.W. Westcot. Irrigation and Drainage Paper 29, Rev. 1. Rome. 174 pp.

FAO. 1985. Environmental management for vector control in rice fields. T. Mather. Irrigation and Drainage Paper 41. Rome.

FAO. 1988. World Agriculture Toward 2000: An FAO Study. N. Alexandratos (ed.). Bellhaven Press, London. 338 pp.

FAO. 1989. Sustainable development and natural resources. 25th Conference of FAO. Document C89/2. Rome.

FAO. 1990. An international action programme on water and sustainable agricultural development. A strategy for the implementation of the Mar del Plata Action Plan for the 1990s. Rome. 42 pp.

FAO. 1992. CROPWAT: a computer program for irrigation planning and management. M. Smith. Irrigation and Drainage Paper 46. Rome.

FAO. 1991. CLIMWAT for CROPWAT - a climatic database. AGLW/FAO, Rome.

Fierotti G., LoCascio B. and Lombardo V. 1984. Effects of irrigation with saline waters in soil and crops. In: Trans. 12th Congress on Irrigation and Drainage, ICID, Fort Collins, Colorado, 28 May - 2 June 1984. pp. 199-214.

Fleming G.A. 1962. Selenium in Irish soils and plants. Soil Sci. 94:28-35.

Frenkel H. and Shainberg I. 1975. Chemical and hydraulic changes in soils irrigated with brackish water under cotton production. Proc. Internat. Symposium on Irrigation with Brackish Water, Beer Sheva, Israel. Negev Press. pp. 175-183.

Goldberg S. and Forster H.S. 1990. Flocculation of reference clays and arid zone soil clays. Soil Sci. Soc. Am. J. 54:714-718.

Goldberg D. and Gornet B. 1971. Drip irrigation agricultural development. Presented at the Internat. Expert Panel on Irrigation-Drip (Trickle) and Automated Pressure Irrigation. Herzilya-on-Sea, Israel, 6-13 September 1971.

Goldberg S., Forster H.S. and Heick E.L. 1991. Flocculation of illite/kaolinite and illite/montmorillonite mixtures as affected by sodium adsorption ratio and pH. Clays and Clay Minerals 39:375-380.

Gornet B., Goldberg D., Rimon D. and Ben Asher I. 1971. The physiological effect of water quality and method of application on a number of field crops: II. The effects of sprinkler and trickle irrigation. J. Amer. Soc. Hort. Sci. (Submitted for publication).

Grattan S.R. and Rhoades J.D. 1990. Irrigation with saline groundwater and drainage water. In: Agricultural Salinity Assessment and Management Manual. K.K. Tanji (ed.). ASCE, New York. pp. 432-449.

Grattan S.R., Shennan C., May D.M., Mitchell J.P. and Burau R.G. 1987. Use of drainage water for irrigation of melons and tomatoes. California Agriculture 41:27-28.

Gupta I.C. 1990. Use of Saline Water in Agriculture. A study of arid and semi-arid zones in India. Revised edition. Oxford and IBH Publishing, New Delhi.

Gupta I.C. and Pahwa K.N. 1981. A Century of Soil Salinity Research in India - Annotated Bibliography 1863-1976. Oxford and IBH Publishing, New Delhi. 400 pp.

Hadas A. and Frenkel H. 1982. Infiltration as affected by long-term use of sodic-saline water for irrigation. Soil Sci. Soc. Am. J. 46:524-530.

Hanks R.J., Neilson R.F., Cartee R.L. and Willardson L.S. 1984. Use of saline waste water from electrical power plants for irrigation. In: Salinity in Watercourses and Reservoirs. R.H. French (ed.). pp. 473-492.

Hatcher J.T., Blair G.Y. and Bower C.A. 1959. Response of beans to dissolved and adsorbed boron. Soil Sci. 88:98-100.

Hoffman G.J. and van Genuchten M.T. 1983. Soil properties and efficient water use: water management for salinity control. In: Limitations to Efficient Water Use in Crop Production. H.M. Taylor *et al.* (eds.). American Society of Agronomy, Madison, Wisconsin. pp. 73-85.

Hoffman G.J., Rhoades J.D., Letey J. and Sheng F. 1990. Salinity management. In: Management of Farm Irrigation Systems. G.J. Hoffman, T.A. Howell and K.H. Solomon (eds.). ASCE, St. Joseph, Michigan. pp. 667-715.

Ingvalson R.D., Rhoades J.D. and Page A.L. 1976. Correlation of alfalfa yield with various indices of salinity. Soil Sci. 122:145-153.

Jain B.L. 1981. Salt balance studies in saline water irrigated soils. J. Indian Soc. Soil Sci. 29:160-166.

Jensen M.E., Rangeley W.R. and Dieleman P.J. 1990. Irrigation trends in world agriculture. In: Irrigation of Agricultural Crops. American Society of Agronomy, Madison, Wisconsin. pp. 31-67.

Jurinak J.J. and Suarez D.L. 1990. The chemistry of salt-affected soils and waters. In: Agricultural Salinity Assessment and Management Manual. K.K. Tanji (ed.). ASCE, New York. pp. 42-63.

Jury W.A. 1984. Field scale water and solute transport through unsaturated soils. In: Soil Salinity under Irrigation. I. Shainberg and J. Shalhevet (eds.). Springer Verlag, New York. pp. 115-125.

Jury W.A., Frenkel H., Fluhler H., Devitt D. and Stolzy L.H. 1978. Use of saline irrigation waters and minimal leaching for crop production. Hilgardia 46:169-192.

Kaddah M.T. and Rhoades J.D. 1976. Salt and water balance in Imperial Valley, California. Soil Sci. Soc. Am. J. 40:93-100.

Kandiah A. 1990. Environmental impacts of irrigation development with special reference to saline water use. In: Water, Soil and Crop Management Relating to the Use of Saline Water. AGL/MISC/16, FAO, Rome. pp. 152-165.

Keren R. and Miyamoto S. 1990. Reclamation of saline-, sodic- and boron-affected soils. In: Agricultural Salinity Assessment and Management Manual. K.K. Tanji (ed.). ASCE, ----- pp. 410-431.

Keren R. and Shainberg I. 1978. Irrigation with sodic and brackish water and its effect on the soil and on cotton fields. Hassade 58:963-976.

Keren R. and Shainberg I. 1984. Colloidal properties of clay minerals in saline and sodic solution. In: Soil Salinity under Irrigation. I. Shainberg and J. Shalhavet (eds.). Springer Verlag, New York. pp. 32-45.

Kruse E.G., Willardson L. and Ayars J. 1990. On-farm irrigation and drainage practices. In: Agricultural Salinity Assessment and Management Manual. K.K. Tanji (ed.). ASCE, New York. pp. 349-371.

Lacey L.A. and Lacey C.M. 1990. The medical importance of riceland mosquitoes and their control using alternatives to chemical insecticides. J. Amer. Mosquito Control Assoc. Supplement 2.

Lagerwerff J.V. and Holland J.P. 1960. Growth and mineral content of carrots and beans as related to varying osmotic and ionic-composition effects in saline-sodic sand cultures. Agron. J. 52:603-608.

Lal R. 1990. Sustainable land and water resources development and management. FAO/Netherlands Conference on Sustainable Agriculture and Rural Development, FAO, Rome.

Lauchli A. and Epstein E. 1990. Plant responses to saline and sodic conditions. In: Agricultural Salinity Assessment and Management Manual. K.K. Tanji (ed.). ASCE, New York. pp. 113-137.

Law J.P., Skogerboe G.V. and Denit J.D. 1972. The need for implementing irrigation return flow control. Proc. Nat. Conf. on Managing Irrigated Agriculture to Improve Water Quality. pp. 1-17.

Letey J. and Dinar A. 1986. Simulated crop-water production functions for several crops when irrigated with saline waters. Hilgardia 54:1-32.

Letey J., Dinar A. and Knapp K.C. 1985. Crop-water production function model for saline irrigation waters. Soil Sci. Soc. Am. J. 49:1005-1009.

Letey J., Knapp K. and Solomon K. 1990. Crop production functions. In: Agricultural Salinity Assessment and Management Manual. K.K. Tanji (ed.). ASCE, New York. pp. 305-326.

Letey J., Roberts C., Penberth M. and Vasek C. 1986. An agricultural dilemma: drainage water and toxics disposal in the San Joaquin Valley. Special Publication 3319, University of California, Oakland.

Maas E.V. 1986. Salt tolerance of plants. Applied Agricultural Research 1:12-26.

Maas E.V. 1990. Crop salt tolerance. In: Agricultural Salinity Assessment and Management Manual. K.K. Tanji (ed.). ASCE, New York. pp. 262-304.

Maas E.V. and Hoffmann G.J. 1977. Crop salt tolerance - current assessment. ASCE J. Irrig. and Drainage Div. 103(IR2):115-134.

Maas E.V. and Nieman R.H. 1978. Physiology of plant tolerance to salinity. In: Crop Tolerance to Suboptimal Land Conditions. G.A. Jung (ed.). ASA Special Publication 32:227-299.

Manchanda H.R. and Chawla K.L. 1981. Salt profile variations and wheat growth under irrigation with highly saline waters on coarse-loamy soils in South Western Haryana. J. Indian Soc. Soil Sci. 29:504-511.

Mashali A.M. 1985. Amelioration and development of deteriorated soils - Egypt. Technical Report, Project FAO/UNDP EGY/79/020. Cairo, Egypt. 1984-1985.

Mashali A.M. 1989. Salinization as a major process of soil degradation in the Near East. 10th Session of the Regional Commission on Land and Water Use in the Near East, Amman, Jordan. 10-14 December 1989.

Mather T.H. 1985. Environmental management for vector control in rice fields. Irrigation and Drainage Paper 41. FAO, Rome.

Meiri A. 1984. Plant response to salinity: experimental methodology and application to field. In: Soil Salinity under Irrigation. I. Shainberg and J. Shalhevet (ed.). Springer Verlag, New York. pp. 284-297.

Meiri A., Plant Z. and Pincas L. 1981. Salt tolerance of greenhouse grown muskmelon. Soil Sci. 131:189-193.

Meiri A., Shalhevet J., Stolzy L.H., Sinai G. and Steinhardt R. 1986. Managing multi-source irrigation water of different salinities for optimum crop production. BARD Technical Report #1-402-91. Volcani Center, Bet Dagan, Israel. 172 pp.

Mikkelson R.L., Page A.L. and Bingham F.T. 1988. Factors affecting selenium accumulation by agricultural crops. In: Selenium in Agriculture and the Environment. L.W. Jacobs (ed.). Special Publication. American Society of Agronomy, Madison, Wisconsin.

Miles D.L. 1977. Salinity in the Arkansas Valley of Colorado. Interagency Agreement Report EPA-IAG-D4-0544. Environmental Protection Agency, Denver, Colorado. 80 pp.

Minhas P.S., Sharma D.R. and Khosla B.K. 1989. Response to sorghum to the use of saline waters. J. Indian Soc. Soil Sci. 37:140-146.

Minhas P.S., Sharma D.R. and Khosla B.K. 1990a. Mungbean response to irrigation with waters of different salinities. Irrig. Sci. 11:57-62.

Minhas P.S., Sharma D.R. and Khosla B.K. 1990b. Effect of alleviation of salinity stress at different growth stages of Indian mustard (*Brassica juncea*). Indian J. Agric. Sci. 60:343-346.

Miyamoto S., Moore J. and Stichler C. 1984. Overview of saline water irrigation in Far West Texas. In: Water Today and Tomorrow. J.R. Replogle and K.G. Renard (eds.). Proc. Speciality Conf. Irrigation and Drainage Division of ASCE, Flagstaff, Arizona, 24-26 July 1984. ASCE, New York. pp. 222-230.

Moore J. and Hefner J.J. 1977. Irrigation with saline water in the Pecos Valley of West Texas. Proc. Internal. Salinity Conf. Managing Saline Waters for Irrigation. Texas Tech. Univ., Lubbock, Texas. pp. 339-344.

National Research Council. 1989. Irrigation-induced water quality problems: what can be learned from the San Joaquin Valley experience. Nat. Acad. Press, Washington DC.

Nimah M.N. and Hanks R.J. 1973. Model for soil water, plant and atmospheric interrelations. I. Description and sensitivity. Soil Sci. Soc. Amer. Proc. 37:522-527.

O'Leary J.W. 1984. High productivity from halophytic crops using highly saline irrigation water. In: Water Today and Tomorrow. J.R. Replogle and K.G. Renard (eds.). Proc. Speciality Conf. Irrigation and Drainage Division of ASCE, Flagstaff, Arizona, 24-26 July 1984. ASCE, New York. pp. 213-217.

Oster J.D. and Rhoades J.D. 1975. Calculated drainage water compositions and salt burdens resulting from irrigation with river waters in the Western United States. J. Environ. Qual. 4:73-79.

Oster J.D. and Rhoades J.D. 1977. Various indices for evaluating the effective salinity and sodicity of irrigation waters. Proc. Internat. Salinity Conf. on Managing Saline Water for Irrigation, Texas Tech. Univ., Lubbock, Texas. pp. 1-14.

Oster J.D. and Rhoades J.D. 1990. Steady state root zone salt balance. In: Agricultural Salinity Assessment and Management Manual. K.K. Tanji (ed.). ASCE, New York. pp. 469-481.

Pal B., Singh C. and Singh H. 1984. Barley yield under saline water cultivation. Plant and Soil 81:221-228.

Pearson G.A. 1960. Tolerance of crops to exchangeable sodium. US Dept. Agric. Info. Bull. 216. 4 pp.

Pearson G.A. and Bernstein L. 1958. Influence of exchangeable sodium on yield and chemical composition of plants. II. Wheat, barley, oats, rice, tall fescue, and tall wheatgrass. Soil Sci. 86:254-261.

Pitcairn M.J., Washino R.K. and Palchik S. 1987. Factors affecting larval mosquito abundance in northern California rice fields. Proc. 55th Annual Conf. of the Calif. Mosquito and Vector Control Association.

Postel S. 1989. Water for agriculture: facing the limits. Worldwatch Paper 93. Worldwatch Institute, Washington DC.

Prasad R. 1967. Survey of the nitrogen rice saline tank and drain waters in the Unnao district of Uttar Pradesh. J. Indian Soc. Soil Sci. Vol. 97-101.

Pratt P.F. and Suarez D.L. 1990. Irrigation water quality assessments. In: Agricultural Salinity Assessment and Management Manual. K.K. Tanji (ed.). ASCE, New York. pp. 220-236.

Raats P.A.C. 1974. Movement of water and salts under high frequency irrigation. Proc. 2nd. Internal. Drip Irrig. Conf., San Diego, California. 7-14 July. pp. 222-227.

Rady A.H.M. 1990. Water, soil and crop management relating to the use of saline water. In: Proc. Expert Cons. on Water Soil and Crop Management relating to the Use of Saline Water, October 1989. AGL/MISC/16/90. FAO, Rome.

Rains D.W., Goyal S., Weyranch R. and Lauchli A. 1987. Saline drainage water reuse in a cotton rotation system. California Agriculture 41:24-26.

Rawlins S.L. 1977. Uniform irrigation with a low-head bubbler system. Agric. Water Management 1:167-178.

Rawlins S.L. and Raats P.A.C. 1975. Prospects for high-frequency irrigation. Science 188:604-610.

Rhoades J.D. 1972. Quality of water for irrigation. Soil Sci. 113:277-284.

Rhoades J.D. 1974. Drainage for salinity control. In: Drainage and Agriculture. J. van Schilfgaarde (ed.). Agronomy 17, American Society of Agronomy. pp. 433-461.

Rhoades J.D. 1977. Potential for using saline agricultural drainage waters for irrigation. Proc. Water Management for Irrigation and Drainage, ASCE, Reno, Nevada, July. 177:85-116.

Rhoades J.D. 1980. Determining leaching fraction from field measurements of soil electrical conductivity. Agric. Water Mgmt. 3:205-215.

Rhoades J.D. 1982. Reclamation and management of salt-affected soils after drainage. Proc. First Annual Western Provincial Conf. Rationalization of Water and Soil Resources and Management, Lethbridge, Alberta, Canada. 29 November-2 December 1982. pp. 123-197.

Rhoades J.D. 1984a. Using saline water for irrigation. Proc. Internal Workshop on Salt Affected Soils of Latin America, Maracay, Venezuela, 23-30 October 1983. pp. 22-52. Publ. in Scientific Review on Arid Zone Research, 1984, Vol. 2, pp. 233-264.

Rhoades J.D. 1984b. Reusing saline drainage waters for irrigation: a strategy to reduce salt loading of rivers. In: Salinity in Watercourses and Reservoirs. R.H. French (ed.). Proc. Internal. Symp. State-of-the-Art Control of Salinity. Salt Lake City, Utah, 12-15 July 1983. pp. 455-464.

Rhoades J.D. 1984c. New strategy for using saline waters for irrigation. Proc. ASCE Irrigation and Drainage Specialty Cong., Water Today and Tomorrow, 24-26 July 1984, Flagstaff, Arizona. pp. 231-236.

Rhoades J.D. 1987a. Principles of salinity control on food production in North America. In: Water and Water Policy in World Food Supplies. W.R. Jordan (ed.). Proc. Conf. 26-30 May 1985. Texas A&M Univ. Press. pp. 141-151.

Rhoades J.D. 1987b. Use of saline water for irrigation. Water Quality Bulletin 12:14-20.

Rhoades J.D. 1988a. Evidence of the potential to use saline water for irrigation. Proc. Symp. Re-use of Low Quality Water for Irrigation. R. Bouchet (ed.). Water Research Centre, Egypt. pp. 133-146.

Rhoades J.D. 1988b. The problem of salt in agriculture. Yearbook of Science and the Future Encyclopaedia Britannica. pp. 118-135.

Rhoades J.D. 1989. Intercepting, isolating and reusing drainage waters for irrigation to conserve water and protect water quality. Agric. Water Mgmt. 16:37-52.

Rhoades J.D. 1990a. Blending saline and non-saline waters reduces water usable for crop production. In: Proc. 1990 Conf. Irrigation and Drainage. S.C. Harris (ed.). 11-13 July 1990, Durango, Colorado. pp. 442-452.

Rhoades J.D. 1990b. Determining soil salinity from measurements of electrical conductivity. Commun. Soil Sci. Plant Anal. 21:1887-1926.

Rhoades J.D. 1992. Instrumental field methods of salinity appraisal. In: Advances in Measurement of Soil Physical Properties: bringing theory into practice. G.C. Topp, W.D. Reynolds and R.E. Green (eds). SSSA Special Publ. 30, ASA, CSSA and SSSA, Madison, Wisconsin. (In press).

Rhoades J.D. and Dinar A. 1991. Reuse of agricultural drainage water to maximize the beneficial use of multiple water supplies for irrigation. In: The Economics and Management of Water and Drainage in Agriculture. A. Dinar and D. Zilberman (eds.). Kluwer Academic Publ. pp. 99-115.

Rhoades J.D. and Loveday. 1990. Salinity in irrigated agriculture. In: Irrigation of Agricultural Crops. B.A. Stewart and D.R. Nielsen (eds.). ASA Monograph. pp. 1089-1142.

Rhoades J.D. and Merrill S.D. 1976. Assessing the suitability of water for irrigation: theoretical and empirical approaches. In: Prognosis of salinity and alkalinity. Soils Bulletin 31. FAO, Rome. pp. 69-109.

Rhoades J.D. and Suarez D.L. 1977. Reducing water quality degradation through minimized leaching management. Agric. Water Mgmt. 1:127-142.

Rhoades J.D., Corwin D.L. and Hoffman G.J. 1981 Scheduling and controlling irrigations from measurements of soil electrical conductivity. Proc. ASAE Irrigation Scheduling Conf., Chicago, Illinois, 14 December 1981. pp. 106-115.

Rhoades J.D., Rawlins S.L. and Phene C.J. 1980. Irrigation of cotton with saline drainage water. ASCE Cong. and Exposition, Portland, Oregon, April 1980. Preprint 80-119.

Rhoades J.D., Ingvalson R.D., Tucker J.M. and Clark M. 1973. Salts in irrigation drainage water. I. Effects of irrigation water composition, leaching fraction, and time of year on the salt compositions of irrigation drainage waters. Soil Sci. Soc. Amer. Proc. 37:770-774.

Rhoades J.D., Oster J.D., Ingvalson R.D., Tucker J.M. and Clark M. 1974. Minimizing the salt burdens of irrigation drainage waters. J. Environ. Qual. 3:311-316.

Rhoades J.D., Bingham F.T., Letey J., Hoffman G.J., Dedrick A.R., Pinter P.J. and Replogle J.A. 1989a. Use of saline drainage water for irrigation: Imperial Valley study. Agric. Water Mgmt. 16:25-36.

Rhoades J.D., Bingham F.T., Letey J., Dedrick A.R., Bean M., Hoffman G.J., Alves W.J., Swain R.V., Pacheco P.G. and LeMert R.D. 1989b. Reuse of drainage water for irrigation: results of Imperial Valley study. I. Hypothesis, experimental procedures and cropping results. Hilgardia 56:1-16.

Rhoades J.D., Bingham F.T., Letey J., Pinter P.J. Jr., Le Mert R.D., Alves W.J., Hoffman G.J., Replogle J.A., Swain R.V. and Pacheco P.G. 1989c. Reuse of drainage water for irrigation: results of Imperial Valley study. II. Soil salinity and water balance. Hilgardia 56:17-44.

Richards L.A. and Wadleigh C.H. 1952. Soil water and plant growth. In. Soil Physical Conditions and Plant Growth. B.T. Shaw (ed.). Agronomy 2:73-251.

Rolston D.E., Rains D.W., Biggar J.W. and Lauchli A. 1988 Reuse of saline drain water for irrigation. Paper presented at UCD/INIFAP Conf. Guadalajara, Mexico. Mach 1988.

San Joaquin Valley Drainage Program. 1990. Fish and wildlife resources and agricultural drainage in the San Joaquin Valley, California. San Joaquin Valley Drainage Program, Sacramento, California.

Savva A.P. *et al.* 1984. Irrigation practices in relation to crop responses, water use and soil salinity (1980-1983). Technical Report No. 6. FAO/UNDP/UAE. FAO, Rome. 45 pp.

Shainberg I. 1984. The effect of electrolyte concentration on the hydraulic properties of sodic soils. In: Soil Salinity under Irrigation. I. Shainberg and J. Shalhevet (eds.). Springer Verlag, New York. pp. 49-64.

Shainberg I. and Letey J. 1984. Response of soils to sodic and saline conditions. Hilgardia 52:1-57.

Shainberg I. and Singer M.J. 1990. Soil response to saline and sodic conditions. In: Agricultural Salinity Assessment and Management Manual. K.K. Tanji (ed.). ASCE, New York. pp. 91-112.

Shalhevet J. 1984. Management of irrigation with brackish water. In: Soil Salinity under Irrigation. I. Shainberg and J. Shalhevet (eds.). Springer Verlag, New York. pp. 298-318.

Shalhevet J., Reiniger P. and Shimshi D. 1969. Peanut response to uniform and non-uniform soil salinity Agron. J. 61:384-387.

Shalhevet J. and Yaron B. 1973. Effect of soil and water salinity on tomato quality. Plant and Soil 39:285-292.

Sinai G., Jury W.A. and Stolzy L.H. 1985. Application of automated flow and salinity control to dilution of saline irrigation water. Irrig. Sci. 6:179-190.

Sinai G., Jury W.A. and Stolzy L.H. 1989. Methods for automated dilution of saline water sources for irrigation. J. Irrig. Drain. Div. ASCE. (In press).

Slayter R.D. 1969. Physiological significance of internal water relations to crop yield. In: Physiological Aspects of Crop Yields. American Society of Agronomy, Madison, Wisconsin. pp. 53-88.

Snellen W.B. 1988. A malaria epidemic caused by *Anopheles ludlowi* in Java in 1933. In: Vector-borne Disease Control in Humans through Rice Agro-ecosystems Management. IRRI/PEEM, Manila.

Solomon K.H. 1985. Water - salinity - production functions. Trans ASAE 28:1975-1980.

Stewart B. and Nielsen D. (eds.) 1990. Irrigation of Agricultural Crops. Agronomy Monograph No. 30. American Society of Agronomy, Madison, Wisconsin. 1218 pp.

Suarez D.L. 1981. Relationship between $pH_c$ and SAR and an alternative method of estimating SAR of soil or drainage water. Soil Sci. Soc. Am. J. 45:469-475.

Suarez D.L. 1982. Graphical calculation of ion concentrations in calcium carbonate and/or gypsum soil solutions. J. Environ. Qual. 11:302-308.

Suarez D.L. 1990. Water quality criteria for irrigation. Proc. Speciality Conf. sponsored by Irrigation and Drainage Division, Water Resource Planning and Management Division, ASCE, University of Delaware, Newark, Delaware, 17-20 July 1989. pp. 57-66.

Suarez D.L. and van Genuchten M.T. 1981. Leaching and water-type effects on ground-water quality. ASCE Irrig. and Drainage Div. J. 107(IR1):35-52.

Suarez D.L., Rhoades J.D., Lavado R. and Grieve C.M. 1984. Effect of pH on saturated hydraulic conductivity and soil dispersion. Soil Sci. Soc. Am. J. 48:50-55.

Szabolcs I. 1985. Salt affected soils as a world problem. In: Proc. Internat. Symp. Reclamation of Salt-affected Soils I. Jinan, China. 13-21 May 1985.

Tanji K.K. 1977. Irrigation tail water management. Water Science Report No. 4014 (1976-1977 Annual Report). University of California, Davis, June 1977.

Thomas J.R., Salinas F.G. and Oerther G.F. 1981. Use of saline water for supplemental irrigation of sugarcane. Agron J. 73:1011-1017.

Tripathi B.R. and Pal B. 1979. Seasonal salt accumulation and tolerance of wheat to saline water in the semi-desert tract of Uttar Pradesh. Indian J. Agric. Sci. 49:206-210.

UN. 1991. World population prospects 1990. Population Studies No. 120. United Nations, New York. 607 pp.

UN. 1990. Global Outlook 2000, An Economic, Social, and Environmental Perspective. United Nations, New York. 340 pp.

Unesco/UNDP. 1970. Research and training on irrigation with saline water. Tech. Report Tun. 5. Unesco, Paris. 256. pp.

UNEP. 1982. Worlds Soil Policy. UN Environment Programme, Nairobi.

UNEP. 1984. General Assessment of Progress in the Implementation of the Plan of Action to Combat Desertification. 1978-84. Mimeo. Governing Council, 12th Session, Nairobi.

US Salinity Laboratory Staff. 1954. In: Diagnosis and Improvement of Saline and Alkali Soil. L.A. Richards (ed.). US Dept. Agric. Handbook No. 60.

van Hoorn J.W. 1971. Quality of irrigation water, limits of use and prediction of long-term effects. In: Salinity Seminar, Baghdad. Irrigation and Drainage Paper 7. FAO, Rome. pp. 117-135.

van Schilfgaarde J. 1976. Water management and salinity. In: Prognosis of salinity and alkalinity. Soils Bulletin No. 31. FAO, Rome.

van Schilfgaarde J. 1979. Environmental and institutional aspects of irrigation agriculture. Trans. ASAE 22:344-350.

van Schilfgaarde J. 1982. The Wellton-Mohawk Dilemma. Internat. J. Water Supply and Mgmt. 6:115-127.

van Schilfgaarde J. and Rawlins S.L. 1980. Water resources management in a growing society. In: Efficient Water Use in Crop Production. T.W. Tibbitts and T.T. Kozlowski (eds.). American Society of Agronomy 12:517-530.

van Schilfgaarde J. and Rhoades J.D. 1984. Coping with salinity. In: Water Scarcity, Impacts in Western Agriculture. E.A. Englebert (ed.). University of California Press 6:157-179.

van Schilfgaarde J., Bernstein L., Rhoades J.D. and Rawlins S.L. 1974. Irrigation management for salt control. J. Irrig. and Drainage Div., ASCE 100(IR3). Proc. Paper 10822. pp. 321-338.

Van't Leven J.A. and Haddad M.A. 1968. Surface irrigation with saline water on a heavy clay soil in the Medjerda Valley, Tunisia. Institute for Land and Water Management Research, Technical Bulletin No. 54, The Netherlands. J. Agriculture, Wageningen 15:281-303.

Wadleigh C.H. and Ayers A.D. 1945. Growth and biochemical composition of bean plants as conditioned by soil moisture tension and salt concentration. Plant Physiol. 20:106-132.

Wagenet R.J. 1984. Salt and water movement in the soil profile. In: Soil Salinity under Irrigation. I. Shainberg and J. Shalhevet (eds). Springer Verlag, New York. pp. 100-114.

Westcot D.W. 1988. Reuse and disposal of higher salinity subsurface drainage water - a review. Agric. Water Mgmt. 14:483-512.

WHO 1982. Manual on Environmental Management for Mosquito Control. WHO Offset Pub. No. 66, Geneva.

World Bank. 1988. World Development Report. Washington DC.

World Commission on Environment and Development. 1987. Our Common Future. Oxford University Press, Oxford.

Worstell R.V. 1979. Selecting a buried gravity irrigation system. Trans. ASAE 22:110-114.

Wu L., Burau R.G. and Epstein E. 1987. Study of selenium accumulation and selenium-salinity cotolerance in turf, forage, and salt march species for crop production in deteriorated soils and water quality improvement in the San Joaquin Valley. Technical Progress Report, UC Salinity/Drainage Task Force. Div. Agric. and Natural Resources, University of California.

Yaron D., Bielorai H., Shalhevet J. and Gavish Y. 1972. Estimation procedures for response functions of crops to soil water content and salinity. Water Resources Research 8:291-300.

Zur B. and Bresler E. 1973. A model for the water and salt economy in irrigated agriculture. In: Physical Aspects of Soil Water and Salts in Ecosystems. A. Hadas, D. Swartzendruber, P.E. Rijtema, Fuchs M. and B Yaron (eds.). Springer Verlag, New York. pp. 395-407.

**FAO TECHNICAL PAPERS**

FAO IRRIGATION AND DRAINAGE PAPERS

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ISBN 92-5-103237-8 ISSN 0254-5284

9 789251 032374

M-56 T0667E/1/11.92/3000